Channel Morphology of Unlogged, Logged, and Debris Torrented Streams in the Queen Charlotte Islands

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FISH/FORESTRY INTERACTION PROGRAM

This study was undertaken as part of the Fish/Forestry Interaction Program (FFIP), a multidisciplinary research study initiated in 1981. The program was started following a series of major winter storms in 1978 that triggered landslides over much of the Queen Charlotte Islands forest land base. Originating on steep slopes, many slides deposited tonnes of debris in streams and on valley flats. The events raised private and public concerns over logging practices on the Islands and prompted the establishment of the 5-year program. Overall objectives of FFIP were:

- to study the extent and severity of mass wasting and to assess its impacts on fish habitat and forest sites.
- to investigate the feasibility of rehabilitating stream and forest sites damaged by landslides.
- to assess alternative silvicultural treatments for maintaining the improving slope stability.
- to investigate the feasibility and success of using alternative logging methods, including skylines and helicopters, and by logging planning to reduce logging-related failures.

The program is jointly funded by direct appropriations from the Canada Department of Fisheries and Oceans, the B.C. Ministry of Forests and Lands (Research Branch), and the B.C. Ministry of Environment and Parks (Fisheries Branch). Participating agencies include the Canadian Forestry Service (Pacific Forestry Centre), and the Forest Engineering Research Institute of Canada (FERIC), Vancouver, B.C.

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ABSTRACT

This study compares the morphology of coastal, gravel-bed streams in two logged, one logged and debris torrented, and two unlogged watersheds in the Queen Charlotte Islands. The influence of both logging and direct mass wasting events on channel morphology and, consequently, on the in-stream physical habitat of salmonids is quantified. The comparison also provides a basis for determining habitat rehabilitation criteria for damaged channels. Pools and riffles are discussed in detail.

Longitudinal profiles of long channel segments indicated that channels in watersheds either logged to the channel banks by old techniques (but not torrented), or logged by more recent methods (but which have experienced direct mass wastage events) result in reduced pool-to-pool spacings, increased riffle heights, and altered pool depths. Increases in stored sediment volumes produce proportionally larger riffles and smaller pools, thus reducing available rearing habitat. No significant differences in pool and riffle characteristics were found between unlogged watersheds and those logged by contemporary techniques and not torrented.

Large organic debris (LOD) appeared to be a major influence on stream morphology. A comparison of reaches indicated that LOD characteristics were altered in older logged and torrented channels, including a shift in the LOD size distribution, with smaller in-channel material being more prevalent. Orientation of material was also altered: more LOD lay parallel to the flow direction, as opposed to the more common diagonal orientation found in unlogged and non-torrented channels. This shift in orientation was responsible for a reduction in channel width and depth variability, reduced sediment texture variability, fewer cut banks, smaller pool areas, and decreased channel stability. These changes resulted in reduced habitat diversity and quality. No morphological differences were detected between unlogged and recently logged (non-mass wasted) reaches.

Results of this study suggest that the architecture of unlogged channels can be duplicated to help rehabilitate streams damaged by mass wasting. LOD should play a major role in rehabilitation, and several recommendations for channel restoration are made.

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1 INTRODUCTION

The Queen Charlotte Islands are characterized by abundant salmon-producing streams (Northcote et al. 1984), large areas of steep terrain underlain by highly erodible bedrock (Alley and Thomson 1978), and several soil types which are prone to mass movement (Wilford and Schwab 1982). The incidence of slope failure is high because the Islands have a predominantly wet climate (Williams 1968) and experience frequent seismic activity (Sutherland Brown 1968). Also, there are vast areas of valuable commercial timber which, for over half a century, have made logging an important economic resource.

The inherent instability of the steep Queen Charlotte Islands hillslopes has been increased locally by logging (Schwab 1983; Gimbarzevsky 1986; Rood 1984). Rood emphasizes the relative importance of mass wasting as the dominant geomorphic process in steep areas and documents a 34-fold increase in the frequency of mass wasting occurrences in logged areas. His results also indicate that there is 43 times more sediment, derived from hillslopes, entering stream channels in logged areas compared to unlogged locations.

The biological impact of slope-derived sediment on salmonid streams of the Queen Charlotte Islands has been assessed by Tripp and Poulin (1986a, 1986b, 1986c). Their results show that fish rearing and overwintering areas are reduced, juvenile survival and smolt production have decreased significantly, and incubation environments have been impaired in logged and mass wasted areas.

Church (1983) discussed the routes of sediment transfer through watersheds in the Queen Charlotte Islands. He identified riffles and bars as the important in-channel storage component of sediment derived from hillslope processes, and thus revealed the important connection between slope and fish studies. Sediment, which is produced at higher than average rates in logged basins, is transported by various slope mechanisms (predominantly debris torrents) into stream channels, where it is then stored in riffles and bars, leading to impaired fish habitat conditions. The geomorphological characterization of these storage sites in unlogged, logged, and debris-torrented watersheds is the focus of the present study.

The pool-riffle-bar is the fundamental morphological unit in gravel and cobble bed channels, with the bar representing the major storage place for traction load sediments moved only sporadically at high flows (Church and Jones 1982). Church and Jones suggest that as sediment loads increase, the bar component will become larger and may advance into the next pool to bury the proximal end of the downstream riffle. Lisle (1982), working in coastal California, confirmed that pools become more riffle-like in response to increased sediment loading from landslides. In the same area, Kelsey (1980) documented a reduction in pool-riffle spacing. All the studies reported a net loss in pool area, and hence in overwintering and rearing habitat, as well as sedimentological changes in each component of the pool-riffle-bar unit. Therefore, because these fundamental morphological features reflect sediment input characteristics and are key components to fish habitats, channel morphological studies provide the direct link between hillslope and biological processes.

In addition to sediment loads, the morphological character of a stream channel is determined by several other factors, including watershed geology, soils, climate, vegetation, and physiography. Another variable that can strongly influence channel architecture is large organic debris (LOD). Several recent studies show that stream morphology -- and sediment storage in particular -- is controlled by specific LOD characteristics (Megahan and Nowlin 1976; Keller and Swanson 1979; Keller and Tally 1979; and Keller et al. 1981). The LOD character (quantity and quality) may be altered by logging and debris torrenting (Toews and Moore 1982b; Swanson et al. 1981), and this is an important independent morphological variable.

In addition to providing the link between hillslope and fish studies, the detailed morphological comparison of unlogged, logged, and mass-wasted watershed streams documents the natural architecture of coastal channels, setting the basis for channel stabilization (stream rehabilitation) guidelines.

The specific objectives of the study were:

- to investigate and compare the channel morphology of several logged, unlogged, and debris-torrented watersheds in the Queen Charlotte Islands using appropriately paired reaches;

- to establish appropriate channel stabilization (habitat rehabilitation) criteria.

Undertaken as part of the Fish/Forestry Interaction Program, the study was conducted within the context of an overall study designed to assess the effects of mass wasting on the fisheries resource in watersheds of the Queen Charlotte Islands, and to explore prescriptive solutions for avoiding or mitigating damage attributed to logging-induced landslides (Poulin 1984).

2 STUDY PROCEDURES AND DESCRIPTION OF THE STUDY AREAS

The study design incorporates a paired watershed approach. This involves comparison of drainage basins with similar biophysical characteristics (climate, geology, soils, vegetation, and morphometry) but different land-use activities and slope stability. The advantages of this approach are twofold. First, because several streams are considered, detailed results are available for a wider range of streams than is possible if the study is restricted to a single watershed. Second, the paired approach enables comparisons to be made over short time periods.

2.1 Study Approach

The study involved three distinct steps:

- selection of suitably paired unlogged, logged, and torrented watersheds;
- comparison of fundamental morphological units; and
- comparison of specific morphological parameters.

Each step required information collected at a different level of detail, or scale of enquiry. The study proceeded, therefore, from a small scale (basin) to increasingly large scale investigations (channel to reach). The linkage between each level of study is shown in Figures 1 and 2.

Within main study watersheds with homogeneous biophysical conditions, smaller areas (sub-basins) were partitioned for studies of relatively long segments of the stream (channel scale studies). Also, within each sub-basin a short section of channel was selected for detailed morphological examination (reach scale studies). The study reaches to be compared are summarized in Table 1 and the pairings are explained in Section 2.3.2. The following sections address each element of the study as outlined in Figure 1.

2.2 Watershed Selection

The validity of channel and reach scale study results depends entirely upon the selection of comparable (paired) watersheds. Before

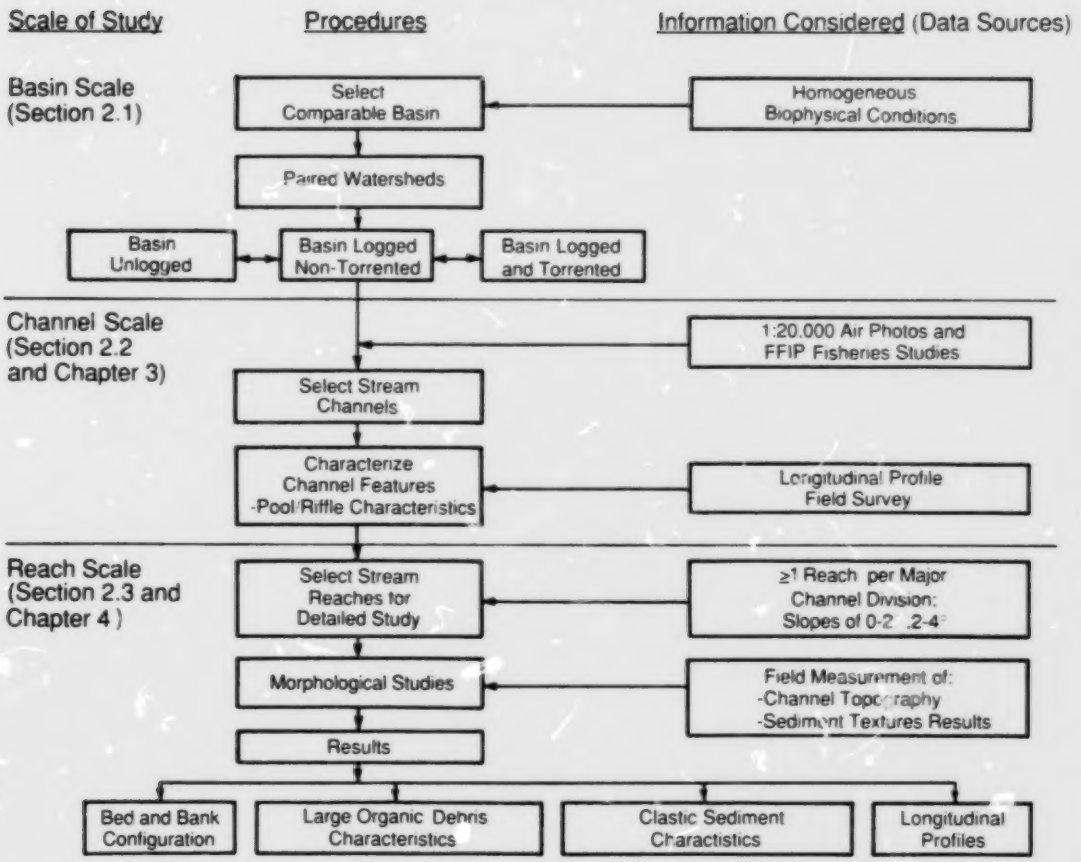
Scale of Study
Procedures
Information Considered (Data Sources)
Basin Scale (Section 2.1)
Select Comparable Basin
Homogeneous Biophysical Conditions
Paired Watersheds
Basin Unlogged
Basin Logged Non-Torrented
Basin Logged and Torrented
Channel Scale (Section 2.2 and Chapter 3)
1:20,000 Air Photos and FFIP Fisheries Studies
Select Stream Channels
Characterize Channel Features -Pool/Riffle Characteristics
Longitudinal Profile Field Survey
Reach Scale (Section 2.3 and Chapter 4)
Select Stream Reaches for Detailed Study
≥1 Reach per Major Channel Division: Slopes of 0-2 .2-4
Morphological Studies
Field Measurement of: -Channel Topography -Sediment Textures Results
Results
Bed and Bank Configuration
Large Organic Debris Characteristics
Clastic Sediment Charactistics
Longitudinal Profiles

FIGURE 1. Channel morphology study procedures.

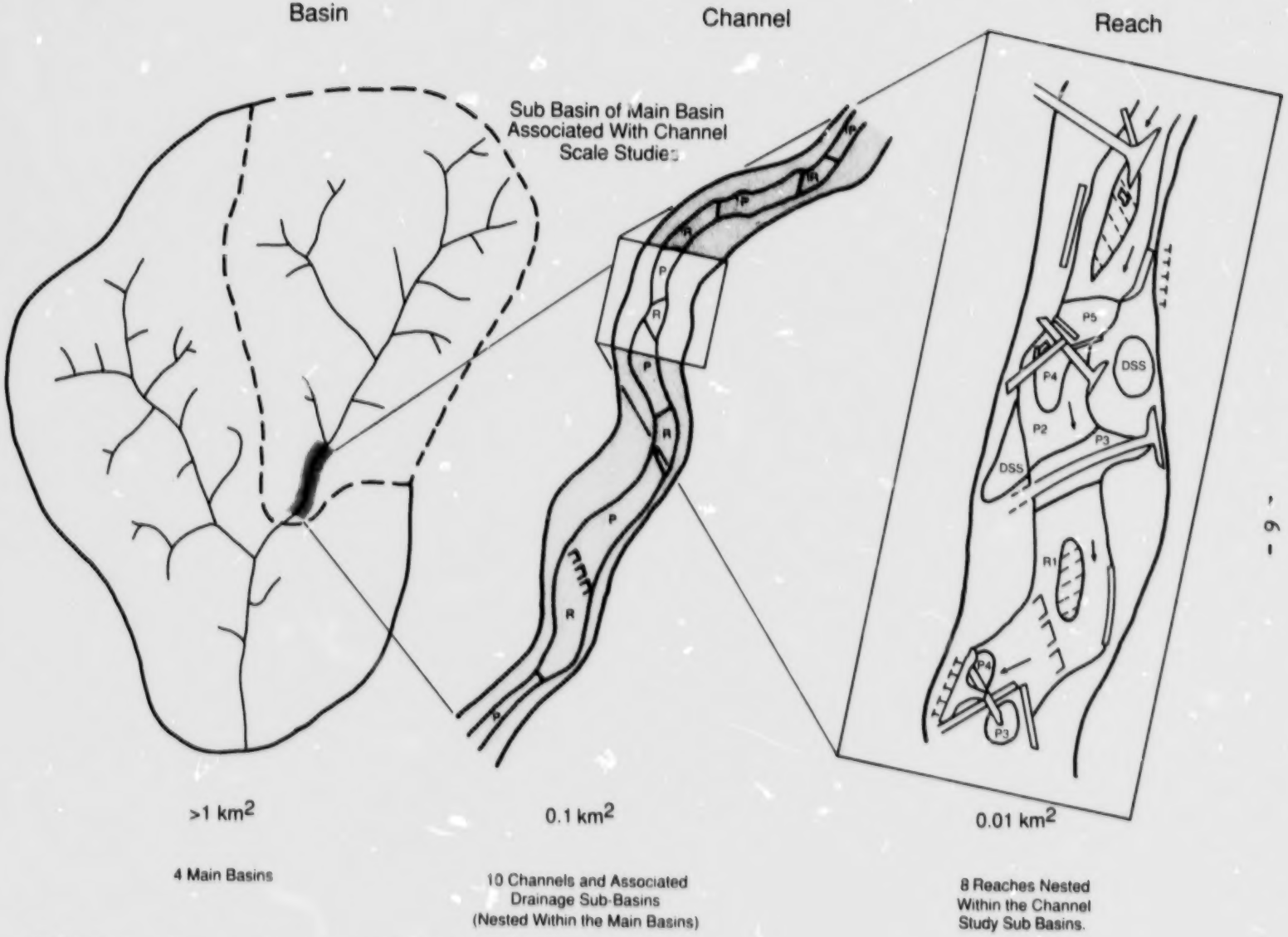

FIGURE 2. Three scales of morphological studies.

TABLE 1. Summary of selected basin, channel, and reach scale study pairs

	Watershed pair[a]		Study design basin type[b]	FFIP stream type[c]
	Unlogged	Logged		
Basin Scale Studies	Government	Mosquito	B	3,2
	Hangover	Bonanza	B	3
		South Bay Dump	C	2
Channel Scale Studies	GA,GB,GC,GD	-	A	3,2
	GB	MM	B	3
	GD	MT	B	2
	GD	SBD	C	2
	Hang	Bonz	B	3
Reach Scale Studies	GB,GC,GD	-	A	3,2
	GB	MM	B	3
	GD	MT	B	2
	GD	SBD	C	2
	Hang	Bonz	B	3

[a] Basin study locations are shown in Figure 3. Channel and reach scale study locations are shown in Figure 3. (Government includes GA, GB, GC, and GD; Mosquito includes MM and MT; and Bonanza includes Hang and Bonz.)

[b] Study design basin types (see Figure 1):
A = tests within basin (internal) variability to ensure that between-basin comparisons are valid (see Section 3).
B = tests between basin variability (unlogged-logged land-use conditions).
C = tests between basin variability (unlogged, debris-torrented conditions).

[c] FFIP stream type 3 = average channel slope <1°.
FFIP stream type 2 = average channel slope 1° - 5°.

it can be concluded that land-use activities have influenced slope stability and channel morphology, basins with similar biophysical conditions and dissimilar land-use histories must be compared. Two basins are considered homogeneous with respect to biophysical conditions if climate, geology, soils, vegetations, and morphometry are similar (Rodda 1976). Because no two watersheds are identical in all aspects, some acceptable degree of similarity must be established and demonstrated quantitatively to substantiate conclusions made at other levels of study (channel and reach scales). A critical review of the biophysical similarity of the basins included in this study is given in Hogan (1985), summarized below.

2.2.1 General description of study watersheds

Four watersheds were selected for study (Figure 3). Two watersheds are within the Queen Charlotte Ranges physiographic unit and two are within the Skidegate Plateau unit near the boundary of the Queen Charlotte Ranges.

Of the channel study segments in the four selected watersheds, only that in South Bay Dump Creek has been directly influenced by debris torrenting. Channel banks, consisting of glacial till overlain by successive landslide deposits, indicate that the basin has a history of slope instability and channel perturbation. The most recent torrent occurred in 1978, originating in the logged headwater, and travelled to the ocean; large depositional zones are evident at the creek mouth and 900 m upstream. Although slope failures and debris torrenting have occurred in all of the other study watersheds, these are confined to upstream zones. Channel morphology studies in these basins address the downstream, indirect influence of slope failures on streams.

The basins to be compared are: 1) Government Creek with Mosquito Creek; 2) Hangover (tributary to Bonanza) with Bonanza Creek (upstream of their confluence); and 3) Government Creek with South Bay Dump Creek.

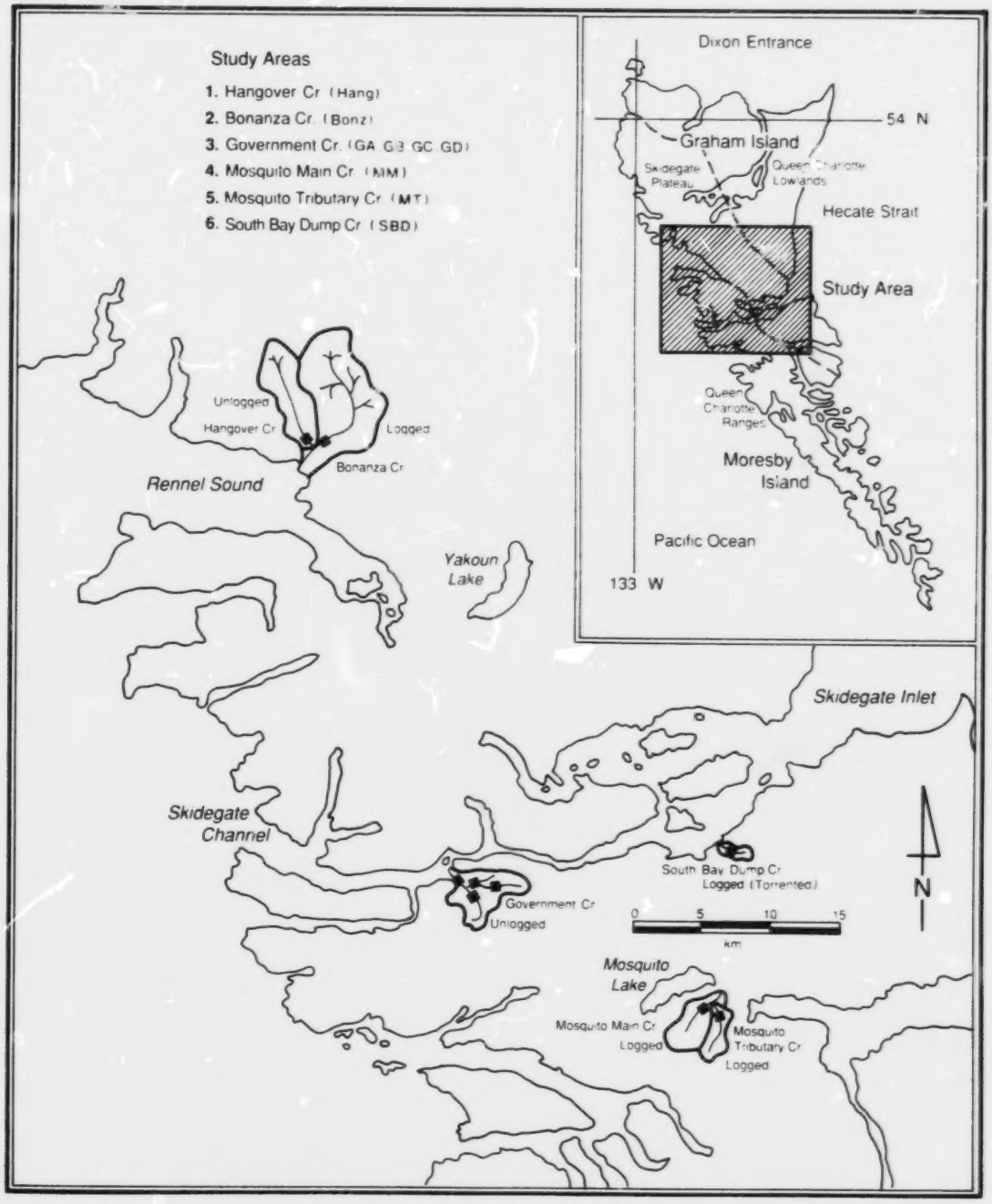

FIGURE 3. Study watersheds on the Queen Charlotte Islands.

2.2.2 Similarity of study watersheds

With the exception of basin morphometry, the environmental setting of each study watershed has been documented in several other reports (Sutherland Brown 1968; Alley and Thomson 1978; Smith et al. 1983; Hogan 1985; Lewis[1]; Banner et al.[2]). Their results are summarized in Table 2a. The comparison basins are similar with respect to geology, precipitation, soils, and vegetation. Minor exceptions include differences in absolute relief between Government Creek and Mosquito Creek watersheds. Bonanza Creek includes its pair (Hangover Creek) and so both are similar in most respects. South Bay Dump Creek is compared with sections of Government and Mosquito (see Section 2.3).

In a comparative study of streams, basin morphometry (gometry and channel network structure) must be examined because channel characteristics are influenced by factors relating to basin shape. Basin morphometry is compared in Table 2b. Of the three combinations of pairs, the Government and Mosquito Creek watershed pair is the most critical because Bonanza is subdivided and comparisons are made between the sub-basins (see Section 2.3). Table 2b indicates that although there are some morphometric differences between the Government and Mosquito Creek watersheds, they are sufficiently similar to constitute a matching pair.

A comparison of linear scale ratios and dimensionless number ratios for the main basins is also given (Table 2b). The ratio for each watershed pair is the unlogged basin value divided by the logged basin value. Considering the Government-Mosquito ratios, all values except mean elevation and shape are within approximately 20% of

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[1] Lewis, T. 1982. The ecosystem of Tree Farm license 24, Queen Charlotte Islands, British Columbia. Report to Western Forest Products, Ltd. Unpubl. mimeograph.

[2] Banner, A., J. Pojar, and R. Trowbridge. 1983. Ecosystem classification of the Coastal Western Hemlock Zone, Queen Charlotte Islands Subzone (CWHq), Prince Rupert Forest Region, British Columbia. B.C. Min. For., Smithers, B.C. Unpubl. manuscript.

TABLE 2. Watershed characteristics of selected Queen Charlotte Island study streams

a) General watershed characteristics: main basins

	Watersheds			
	Government Creek (Gov't)	Mosquito Creek (Mosq)	Bonanza Creek (Bonz)	South Bay Dump Creek (SBD)
Total areas (km^2)	16.2	17.3	88.5	3.9
Absolute relief (m)	520.0	1110.0	730.0	550.0
Stream length (mainstem, km)	5.1	6.4	16.0	3.3
Stream order[a]	4	4	5	3
Geology[b]	Recent Alluvium Triassic Basalt	Recent Alluvium Triassic Basalt	Paleocene Basalt	Crateceous sedimentary, sandstones, colluvium, moraine
Surficial materials[c]	outwash sands and gravels	colluvium, moraine lacustrine	colluvium, moraine, estuarine	
Precipitation (mm yr^{-1})[d]	≥ 3665	≥ 3665	≥ 3665	≥ 3665
Soils[e]	podzols	podzols	podzols	podzols
Vegetation[f]	w. hemlock, w. redcedar, shore pine	w. hemlock Sitka spruce, w. redcedar	w. hemlock, redcedar, shore pine	w. hemlock, redcedar, shore pine
Land use/hillslope stability	unlogged	logged	logged	logged & torrented

b) Comparisons of main basin morphometric characteristics: ratios of selected linear scale features and dimensionless numbers.

Watershed pairs	Linear scale ratios[g]			Dimensionless number ratios[h]				
	L_2	D	R	R_b	C_L	S_h	HI	S_1
Main basins								
Bonz/Mosq	1.12	1.05	1.53	1.38	0.80	1.31	1.35	0.67
Gov't/Bonz	0.76	0.88	0.56	0.61	0.83	0.39	0.86	0.79
Gov't/Mosq	1.18	0.92	0.44	0.84	0.66	0.51	0.85	0.79

Notes:

[a] Strahler ordering based on 1:15 000 - 1:20 000 topographic maps and air photographs.
[b] From Sutherland Brown (1968) - prominent rock type.
[c] From Alley and Thompson (1978); Lewis, 1982; Peril Geotechnic Services. 1979. Geotechnic inventory - Rennell Sound, Queen Charlotte Islands. Unpubl. report prepared for Queen Charlotte Timber Ltd., Vancouver, B.C.
[d] From Hogan (1985).
[e] Estimates based on Smith et al. (1983).
[f] Estimates based on Banner et al., 1983.
[g] Linear scale ratios (unlogged basin value divided by the logged/torrented basin value) included:
L_2 = mean length of second-order stream
D = drainage density
R = mean basin elevation

[h] Dimensionless number ratios include:
R_b = geometric bifurcation ratio
C_L = longitudinal profile concavity
S_h = geometric shape factor
HI = hypsometric integral
S_1 = mean slope

unity. The shape ratio value of 0.51 indicates that Mosquito Creek is a relatively long, narrow basin in comparison to Government. Although the mean elevation ratios are considerably different, both hypsometric integral (HI) values are generally low. The similar HI ratios indicate that both basins have fairly large proportions of the drainage basin area at relatively low elevations, while the Mosquito basin includes a relatively isolated high summit.

2.3 Channel Scale Studies

Channel scale studies were undertaken to examine longitudinal profiles, characterize the morphology of each channel, and select study stream reaches (Figure 1). Because pools and riffles are features with length dimensions comparable to channel width, characterization of their spatial nature requires survey distances in excess of at least 20 channel widths.

It was important that the selected channel sections have contributing drainage areas (sub-basins) that are similar to their comparison basins. The following quantifies the degree of sub-basin similarity and presents the field and analytical methods used in these studies.

2.3.1 General description of study channels

Ten stream channel segments were selected for study of pool and riffle characteristics (Figure 3). Longitudinal profiles covering approximately 11.3 km in total length, averaging approximately 1 km per segment, were surveyed in the field. All channels have cobble or gravel beds, have gradients less than 0.0500 and all are less than fifth order (classified according to Strahler [1954] and based on 1:15 000 to 1:21 000 topographic maps).

The Government Creek and Hangover Creek watersheds were unlogged at the time field studies were conducted in 1982. Logging activities in the other study watersheds were reviewed by analyses of B.C. Ministry of Forests and Lands Continuous History Maps and air photographs. The

date, method, and extent of logging are summarized in Table 3. Logging in both Mosquito Creek sub-basins was conducted by methods considered obsolete by today's logging standards. Contemporary techniques were used in the Bonanza Creek watershed.

2.3.2 Similarity of study channels and associated sub-basins

Channel and associated sub-basin characteristics of the 10 study sites are summarized in Table 4. The initially paired channels have similar geologies, precipitation regimes, stream orders, and average gradients; dissimilarities are evident in the drainage basin areas of the Hangover-Bonanza and Government Reach B (GB) and Mosquito Main (MM) pairs.

The channel and sub-basin morphometries are compared in Table 5. It is difficult to establish quantitatively the degree of similarity between two sub-basins. It is evident (Table 5) that differences in both linear scale features and dimensionless number ratios exist between two sub-basins which appear, in most other respects, to be similar. For example, although Government sub-basins B and C are relatively similar (Table 4), there are several morphometric ratios that are substantially different than 1.0 (Table 5). Therefore, to determine if morphometric parameters are similar, it is necessary to consider the variability of the parameters between several biophysically homogeneous sub-basins. The three Government Creek reaches provide the only available estimate of within basin morphometric variability. In selecting comparable sub-basins, the pairs are assumed to be similar if the morphometric ratios do not differ by more than 1 standard deviation.

After allowing for a departure of 1 standard deviation, it is evident (Table 5) that all pairs have similar mean length of second-order streams (L_2) and drainage density (D) ratios, but dissimilar relative relief (R) ratios. Considering the GB/MM pair, the sub-basins are similar with respect to geometric shape factor

TABLE 3. Logging histories of the study watersheds associated with channel scale studies

Watershed	Basin area (km^2)	Date logged	Area km^2	% Basin logged	Road length km	Road length km/km^2	Logging method	Logging to channel bank
Mosquito Main (MM)	11.9	1940's	1.60	13.5	2.06	0.17	Skidded	Yes
		1960's	5.17	43.4	15.47	1.30	High lead	Yes
		Total	6.77	56.9	17.50	1.47		
Mosquito Tributary (MT)	5.4	1960's	1.76	32.6	5.06	0.94	High lead	Yes
South Bay Dump (SBD)	3.9	1960's-1980's	3.08	78.7	6.92	1.77	High lead	Yes
Bonanza (Bonz)	68.3	1975-1982	7.52	11.01	31.54	0.46	High lead	No

TABLE 4. Channel and sub-basin characteristics of the study streams

	Basins									
	Pair						Pair			
	Government Creek				Mosquito Cr.		Hangover Cr.	Bonanza Cr.		South Bay Dump Cr.
Sub-basins[a]	GA	GB	GC	GD	MM	MT	Hang	A	B	SBD
Channel lengths (m)	476	981	697	575	1251	479	1844	1692	451	900
Contribution area (km^2)	16.2	6.9	6.8	3.9	10.5	5.4	20.2	68.3	45.2	3.9
Stream order[b]	4	3	4	3	3	3	4	5	4	3
Average gradient[c]	0.0080	0.0125	0.0199	.0207	.0092	.0191	0.0125	0.0034	0.0065	0.0490
Geology[d]	Uncon.	Uncon.	Uncon.	Volcanics	Uncon.	Volcanics	Volcanics	Uncon.	Volcanics	Sedimentary
Land use/hillslope stability	---------- Unlogged ----------				Logged		Unlogged	Logged		Logged and direct torrented
	---------- Upstream slope failures entering the channel ----------									
Pairs										

[a] Sub-basin locations are shown in Figure 4.
[b] Strahler ordering, based on 1:15 000 - 1:21 000 topographic maps and air photographs.
[c] Average gradients are based on field surveys of channel sections, not the entire stream length.
[d] From Sutherland Brown (1968), prominent rock type of watershed; "Uncon." refers to unconsolidated Quaternary sediments.

TABLE 5. Comparison of sub-basin characteristics: ratios of selected linear scale features and dimensionless numbers[a]

Sub-basin pairs	Linear scale ratios[b]			Dimensionless number ratios[c]			
	L_2	D	R	C_L	S_h	HI	S_1
Sub-basin comparison							
GB/GC	1.56	1.39	0.90	1.03	1.60	1.77	1.25
GB/GD	1.79	1.33	0.97	1.18	1.50	0.77	0.81
GC/GD	1.15	0.96	1.08	1.14	0.94	0.99	0.65
$\bar{X}$	1.50	1.23	0.98	1.12	1.35	1.18	0.90
S	0.32	0.23	0.09	0.08	0.36	0.53	0.31
GB/MM	0.83	0.87	0.40	0.73	0.95	1.26	0.61
GC/MM	0.87	0.82	0.44	0.71	0.62	1.63	0.49
GC/MT	0.89	1.09	0.45	0.71	0.33	1.24	0.47
GD/MT	0.78	1.14	0.42	0.62	0.35	1.25	0.72
GD/SBD	1.09	0.92	0.88	3.55	0.53	0.81	
Hang/Bonz	0.84	0.80	1.0	0.72	0.85	1.33	1.18

[a] Detailed results are included in Hogan (1985).
[b] Linear scale features: L_2 = mean length of second-order streams
D = drainage density
R = relative relief

[c] Dimensionless numbers: C_L = longitudinal profile concavity
S_h = geometric shape factor
HI = hypsometric integral
S_1 = geometric mean basin slope

$\bar{X}$ = arithmetic average
S = standard deviation

(S_h) and hyposemtric integral (HI), but dissimilar in geometric mean basin slope (S_l). The GC/MM pair dimensionless number ratios are dissimilar. Considering GD and MT, all dimensionless number ratios are similar, with the exception of S_h. Only longitudinal profile concavity (C_L) and S_h differ between GD and SBD. The Hang/Bonz sub-basin pair is similar in all respects.

Based solely upon morphometric analyses, the most appropriate pairing of unlogged and logged channels and sub-basins is as follows

Unlogged	Logged	Torrented
Government Channel B(GB)	Mosquito Main (MM)	
Government Channel D(GD)	Mosquito Tributary (MT)	
Government Channel D(GD)		South Bay Dump (SBD
Hangover (Hang)	Bonanza (Bonz)	

The most appropriate within-basin comparisons are Government reaches B with D and B with C.

2.3.3 Methods

Field Methods - longitudinal profiles

To determine the general longitudinal form and characteristics of pools and riffles over a large proportion of each stream, a longitudinal profile survey was conducted. Surveys extended from low gradient (<1°), beginning at or near sea level, through moderate gradient channels (1-5°). Survey equipment included automatic level, stadia rod, and surveyor's hip chain. Slope was calculated from field survey data as the difference in elevation over the horizontal distance. All surveys followed the thalweg; the rodman measured water surface elevations by direct reading. Survey points were not evenly distributed along the channel, but located according to breaks in bed topography associated with pools (low areas) and riffles (high areas), the primary habitat elements. The standard field method (Figure 4a) varied only in the presence of LOD steps (Figure 4b) and high-gradient riffles (Figure 4c). Areas of the

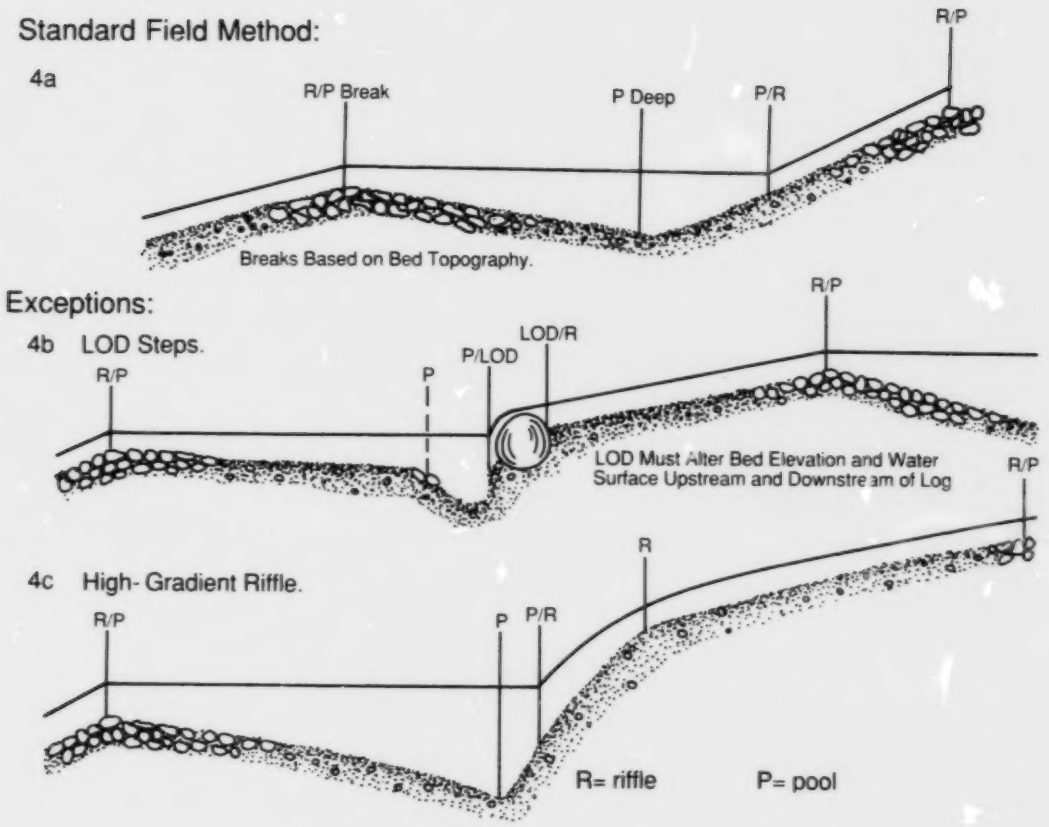


FIGURE 4. Diagram of methods of conducting longitudinal profile surveys.

channel that did not fall clearly into pool or riffle categories were designated as glides and runs; the former more closely resembling a pool than a riffle and the latter more closely resembling a riffle.

Other field observations included the influence of LOD on bed and bank erosion, and characterization of channel pattern, bed and bank materials, and valley configuration.

Analytical Methods - pools and riffles

Longitudinal profiles were analyzed so that both the spacing and relief of pools and riffles in each stream channel could be characterized. The methods used to determine riffle spacing, height, steepness, and relative pool depths are presented in Figure 5.

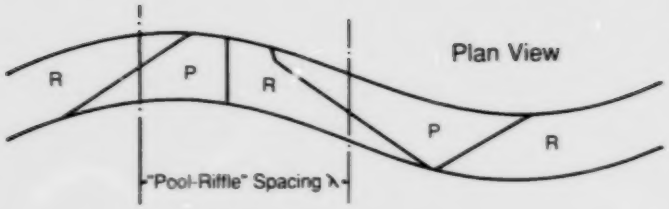
2.4 Reach Scale Studies

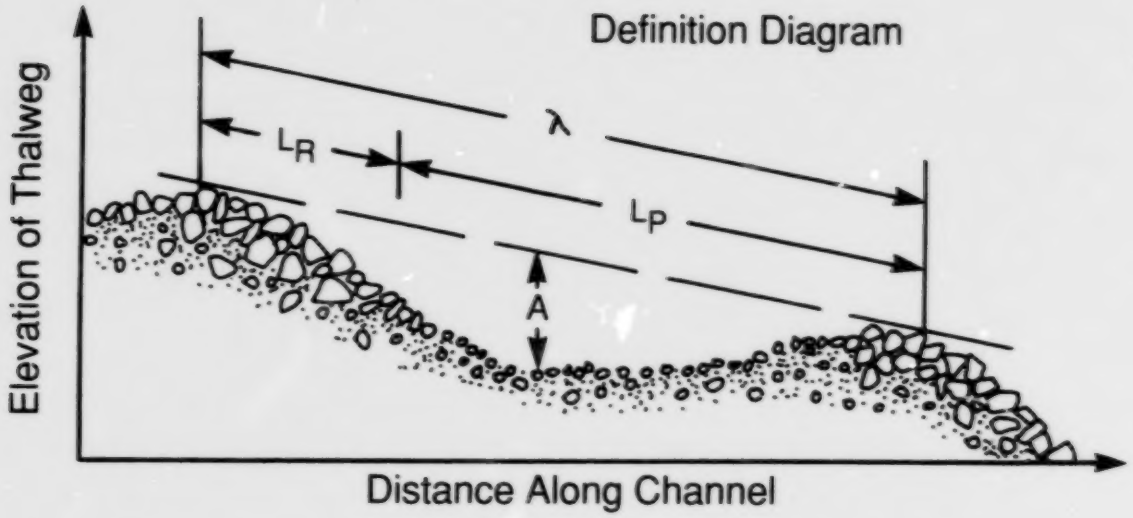
Reach scale studies involved more detailed morphological investigations of specific stream reaches.

2.4.1 Detailed study reach characteristics

A minimum of one reach was selected within each sub-basin (Figure 1). Reach selection was based upon several criteria. First, the reach had to be included in the FFIP fisheries habitat inventories. Second, the study sites had to have comparable channel gradients. Because the basins and sub-basins selected were similar with respect to biophysical properties, the detailed study reaches could be placed anywhere within the sub-basin, but logistics and compliance with the above criteria made random placement impossible.

The physical characteristics of each study reach are summarized in Table 6. The reach lengths ranged from approximately 200 to 460 m. Channel width and median surface sediment size values differred between reaches, reflecting differences in channel and sub-basin properties, particularly in drainage basin areas; these data were used to standardize results in the subsequent analyses.





λ=Pool-Riffle Spacing
A=Riffle Height
L_R=Riffle Length
L_P=Pool Length

$\frac{A}{L_R}$ =Riffle Steepness

$\frac{A}{L}$ =Relative Pool Depth

FIGURE 5. Schematic diagram of pool and riffle sequence and method of determining riffle spacing, height, steepness, and pool depth.

TABLE 6. Detailed study reach characteristics

	Stream reaches							
	Sub-basin pair						Sub-basin pair	
	Government Creek			Mosquito Cr.		South Bay Dump Cr.	Hangover	Bonanza Cr.
Sub-basins[a]	GB	GC	GD	MM	MT	SBD	Hang	Bonz
Average reach gradient	0.0133	0.0150	0.0244	0.0096	0.0194	0.0366	0.0071	0.009
FFIP stream type (unit)[b]	3	3	2	3	2	3	3	3
D_{50} (mm)[c]	30	43	77	51	74	57	57	34
Mean bankfull width (m)	20.2	21.1	18.8	37.6	27.7	21.0	29.3	45.4
Sinuosity[d]	1.10	1.09	1.06	1.10	1.20	1.04	1.44	1.14

[a] Sub-basins are shown in Figure 3.
[b] FFIP stream type 3 = average channel slope <1°.
FFIP stream type 2 = average channel slope 1-5°.
[c] D_{50} = surface sediment, median b-axis.
[d] Sinuosity = thalweg length/reach length.

2.4.2 Methods

Detailed morphological investigations were conducted at low stream flow to determine longitudinal gradients, planimetric form, and sedimentological characteristics.

Longitudinal Profiles

The longitudinal profiles of reach thalwegs were surveyed following the same procedure as the longer channel surveys, but included elevations and distances for all topographic breaks. Successive surveys points did not exceed 10 m separation. This method provided a detailed longitudinal profile and permitted evaluation of clastic sediment storage.

In-Channel Topography and Bed Configuration

Detailed mapping of the morphological features within each study reach was accomplished by theodolite, stadia rod with level, and fibre measuring tape. Surveys were conducted by establishing bench marks in overbank areas and a series of head-pins within the active channel zone. These were tied to bench mark elevations established during the channel scale surveys. Surveyed channel cross-sections were oriented along specific features (such as in line with a riffle that diagonally crossed the channel, or following the alignment of sediment trapped behind LOD), as well as normal to the channel. Local accumulations of sand or isolated back channel pools were located and recorded for mapping.

Topographic maps were drawn at scales of 1:100 to 1:500. Oblique photographs were taken at each head-pin to supplement mapping.

Large Organic Debris

Plan form maps drawn at 1:500 scale were used in the field to map LOD pieces. Mapping was based on the known position of

each cross-sectional transect, bench marks, and head-pins. The length of each LOD piece and diameters at both ends were measured; volumes were estimated by assuming a cylindrical log shape. The volume of root wads (attached or free) was estimated separately. The amount of bark, branches, and moss on each piece was recorded as an indication of the time the material had been in the channel. Trees growing on in-channel large organic debris were cored with an increment borer to determine the minimum LOD residence time. The influence of LOD in forming steps or banks and in directing stream flow was documented.

Sediment Characteristics

Clastic sediment characteristics within each study reach were examined in the field. Surface and sub-surface samples were obtained from side channel bar top locations; in all cases this material was subject to reworking during high flow events.

Standard techniques were used to sample surface sediments (see Wolman 1954; Kellerhals and Bray 1971). Sampling was restricted to stones with a b-axis greater than 8 mm. Sample sizes ranged between 60 and 90 particles. The b-axis measurements were arranged into half phi classes on the basis of frequency by number.

Sub-surface sediment was sampled at one site within each reach, usually coinciding with a surface sediment sampling location. The general sampling procedure involved removing the surface sediment layer, excavating approximately 80 kg of sediment, and sieving and weighing in the field to determine the proportion of the total sample falling into half phi intervals. A sample split was returned to the laboratory for analysis of the fine fraction.

In-channel bulk samples were obtained from the riffle-pool break, by use of a McNeil sampler (McNeil 1960). This technique involves the collection of both surface and sub-surface

sediments. The sampling technique is detailed by Tripp and Poulin 1986c. Standard laboratory techniques were used to analyze the sediment. The material was sieved into a combination of phi and half phi intervals.

The areal sorting of sediment was assessed by visual inspection. At each surveyed cross-section (usually spaced approximately 10 m apart), the channel surface was characterized as to relative proportion of sand, gravel, cobbles, and boulders. A qualitative stability rating was also assigned (see Figure 9). A minimum of three estimates were made per transect. Stability indices and sediment texture were mapped according to these estimates and supplemental field information. Additional detail was gained from photographs.

The calculation of sediment volumes stored along each reach was based on surveyed topographic maps (1:200) made from the field surveys. Determination of the depth of each deposit was often difficult. The thickness of sediment stored behind LOD was assumed to be equal to the distance from the deposit top to the elevation at the base of the debris piece (based on the diameter of the LOD, if the base was not visible). The deposit length was calculated from the LOD upstream to the point where a line of average reach slope would intersect the channel surface. In cases where no deposit base was evident, such as in side and mid-channel gravel bars, the thickness was measured from the deposit top to the water surface elevation at zero discharge. Because the thickness of a deposit is thus determined by the elevation of the riffle thalweg, this represents a conservative (lower value) estimate. Widths and surface expressions of the deposit were taken directly from the compiled topographic maps.

2.5 Summary

The comparison of all study areas is summarized in Table 7. It is apparent that the study pairs are similar in most respects, but minor differences do exist. The importance of these differences is assessed in Section 5.

TABLE 7. Factors not related to logging activities which may contribute to channel changes

	Channel comparison[a]			
General logging status	Contemporary logging techniques	Old logging techniques		Old logging techniques
General mass movement status	not torrented	not torrented		torrented
Comparison streams	Hang, Bonz	GD,MT	GB,MM	GD, SBD
Sub-basin climate				
Precipitation	0	0	0	0
Sub-basin biophysical conditions				
Bedrock geology	0	0	0	0
Surficial geology	0	0	0	0
Soils	0	0	0	0
Vegetation	0	0	0	0
Sub-basin morphometries[b]				
A_d (basin size)	1	0	0	0
L (channel network)	0	1	1	1
R (basin relief)	0	0	1	0
S_h (basin shape)	0	1	0	1
S_l	0	1	1	
C_l (index of valley bottom extent)	1	1	1	1
HI	1	0	0	0
Channel scale studies				
Channel gradients	1	0	0	1
Reach scale studies				
Channel gradients	0	0	0	1
Total qualitative differences	4	5	4	5

[a] Differences are denoted as follows:
0 = no apparent differences 1 = apparent differences

[b] A_d = drainage basin area
L = length of channel segments
R = relative relief
S_h = basin shape
S_l = basin slope
C_l = basin concavity
HI = hypsometric integral

3 CHANNEL SCALE STUDIES

There have been very few previous studies addressing the change in pool and riffle characteristics (proportions, spacing, shape) resulting from debris torrenting and logging-related activities. However, since pool, riffle, and bar characteristics exhibit regular patterns (Leopold et al. 1964), are independent of both channel pattern (Keller and Melhorn 1973) and channel materials (Keller and Melhorn 1978), and are sensitive to sediment loading (Kelsey 1980; Church and Jones 1982; Lisle 1982;), they are ideal indicators of a stream's response to land-use changes. In this section, pool, riffle, and bar characteristics of streams in logged and torrented areas are compared with those in unlogged areas.

Results are based upon analysis of the longitudinal profiles presented in Figures 6 and 7. Summarized results for paired channels and statistical procedures are presented. Complete results are included in Appendix 1. All frequency distributions were normally distributed, as shown by the application of Kolmogorov-Smirnov goodness of fit tests. One-way analysis of variance (ANOVA) tests were then used to determine if significant differences exist in morphological features between unlogged and logged channel pairs. By evaluating the variance of pool and riffle proportions, spacing, and shape within the Government Creek watershed (four channels), it was concluded that the within-basin variance is insignificant and, therefore, between-basin comparisons are valid.

3.1 Pool-Riffle Proportions

The longitudinal profiles (Figures 6 and 7) were partitioned into pools, riffles, glides, and runs. The length of each type was totalled and expressed as a percentage of the total surveyed length (Table 8; Appendix 1, Table A1).

Pools are the most prevalent morphologic unit in Government Creek, with the largest proportion in Government Reach A (60%) and between 47 and 50% pools in Government Reaches B, C, and D. Riffles are proportionally longer than pools in Mosquito Creek. Riffles constitute almost 86%

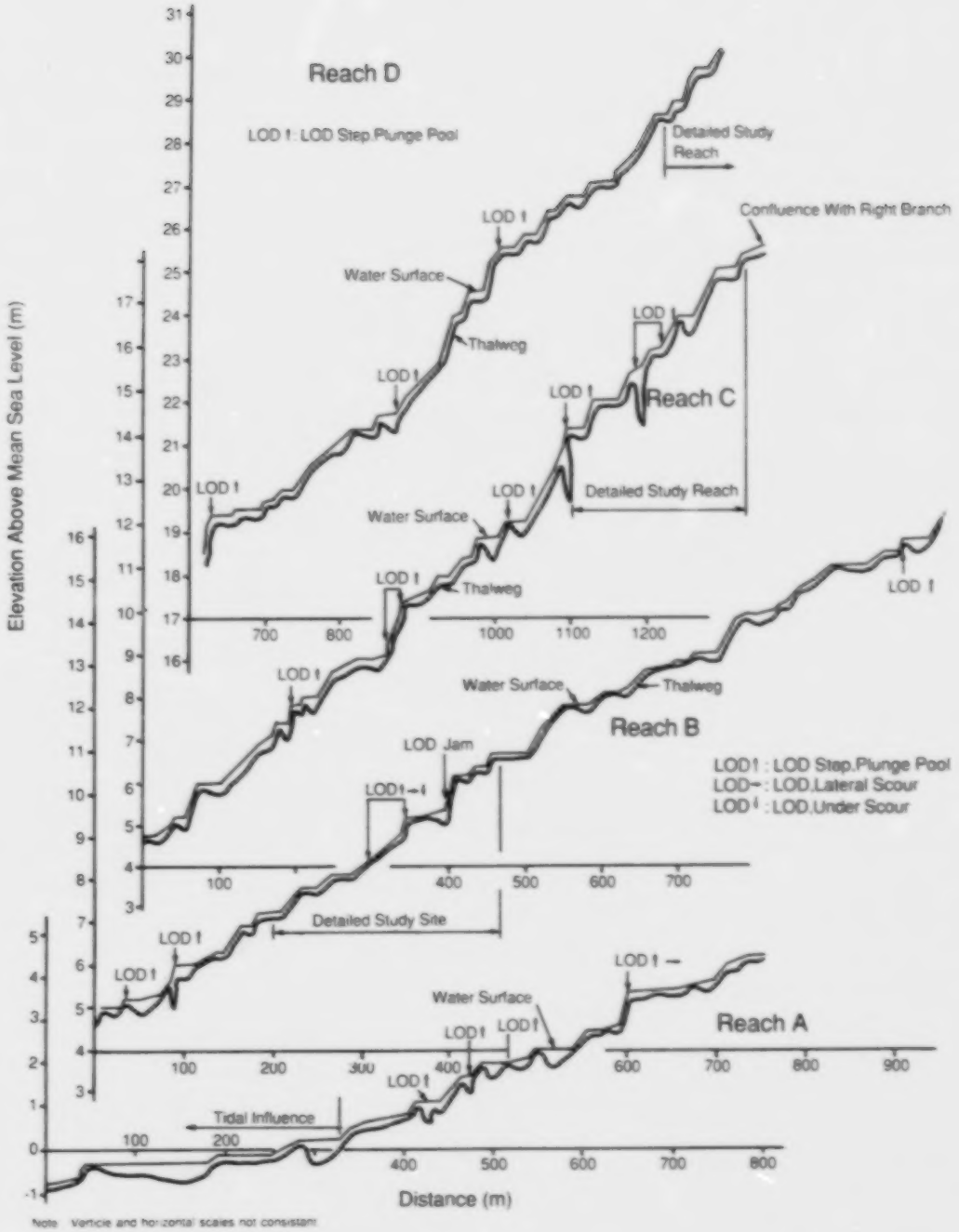


FIGURE 6. Longitudinal profile of channel thalweg: Government Creek.

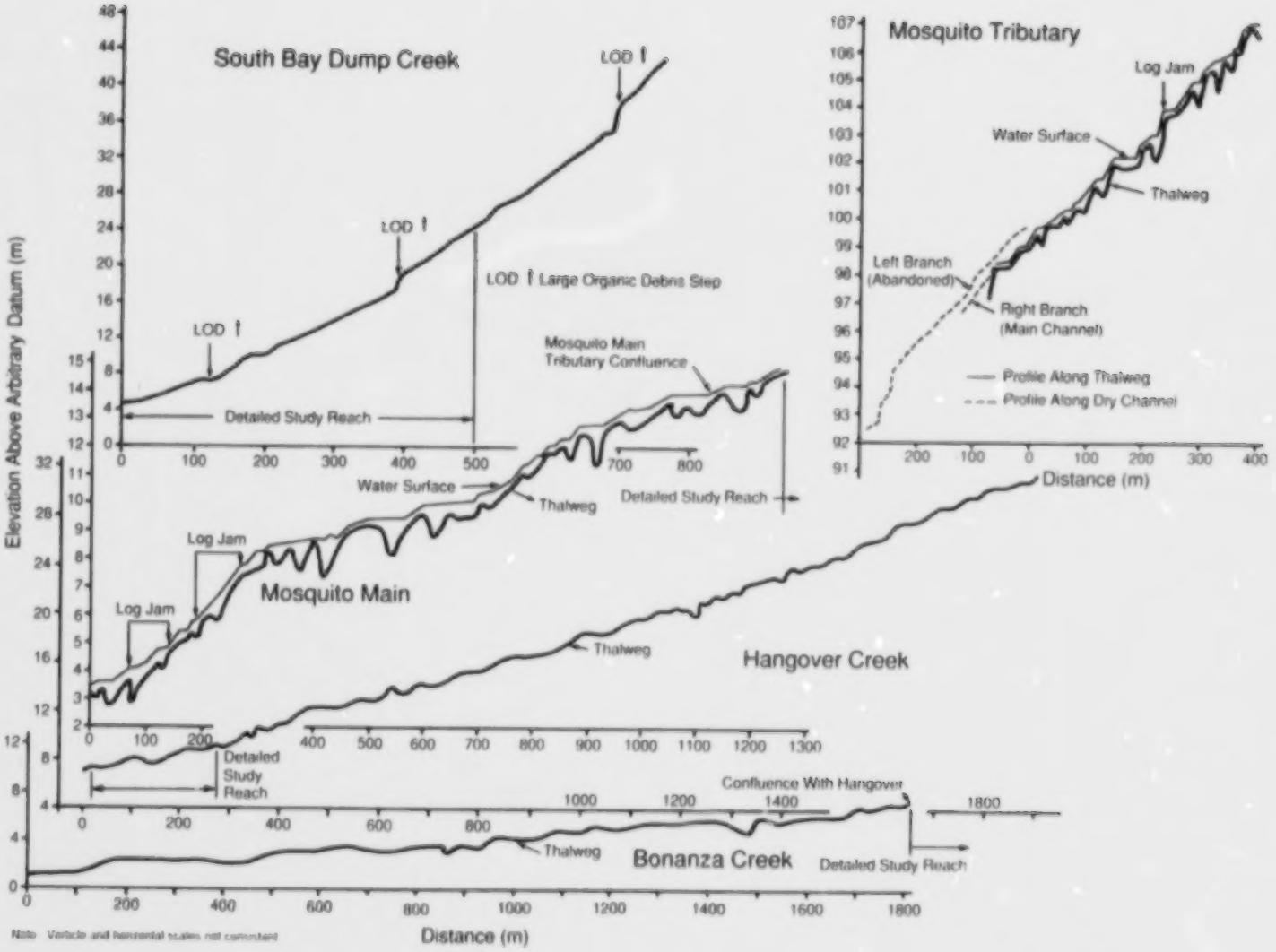


FIGURE 7. Longitudinal profile of channel thalweg: Bonanza, Hangover, Mosquito, and South Bay Dump Creek.

TABLE 8. Pool and riffle proportions[a]

Channel pairs	GB	MM	GD	MT	SBO	Hang	Bonz
Logging/slope failure status	Not logged	Logged	Not logged	Logged and torrented		Not logged	logged
Pool (% of channel length)	47	28	48	33	10	22	52
Riffle (% of channel length)	24	52	37	57	85	37	35
Glide (% of channel length)	15	14	11	6	3	24	7
Run (% of channel length)	14	6	3	4	2	17	10
Pool/riffle ratio $\sum_{i=1}^{n} LP_i / \overline{LR}_i \Big/ n$	3.01	1.33	4.43	0.94	0.27	1.52	2.17
Survey length (m)	981	1251	575	479	471	1844	2143
Comments	Pools are significantly larger than riffles ($\alpha = 0.05$) in unlogged reaches		Pools are significantly larger than riffles in unlogged reaches compared to logged and torrented reaches			No significant differences	

[a] See Tables A1 and A2 in Appedix 1 for complete results.

of channel length in South Bay Dump Creek. Hangover Creek has more riffles than pools, but glides and runs which represent intermediate morphologies between pools and riffles are also important. Combining pools with glides and riffles with runs, and grouping reaches into pairs (Table 8; Table A1 in Appendix 1), it is evident that pool type morphologies cover approximately 62% of the surveyed reaches in Government Creek compared to only about 40 and 15% in Mosquito Creek and South Bay Dump Creek, respectively. Approximately 46% of the stream length surveyed in Hangover Creek is characterized by pools, compared to 59% pool length in Bonanza. This reversal in form (more pool length in the logged stream) indicates the importance of basin morphometry. In all cases the steeper watersheds (Mosquito, Hangover, and South Bay Dump) have longer lengths of riffle.

Pool and riffle proportions calculated as a percentage of the total survey length are conventionally reported in fish habitat studies. However, to determine if significant differences in proportions exist between stream channels it is necessary to assess the variability in all individual pool/riffle ratios. That is, assess:

$$\sum_{i=1}^{n} \left(\frac{L_{P_i}}{L_{R_i}} \right) / n$$ as opposed to

$$\sum_{i=1}^{n} L_{P_i} \Big/ \sum_{i=1}^{n} L_{R_i}$$; where n is one pool or riffle

(see Figure 5). The mean pool/riffle ratios are presented in Tables A1 and A2 in Appendix 1 and are summarized in Table 8. It is apparent that a significant difference exists between pool/riffle ratios in two of three unlogged and logged channel pairs considered (Table 8). These results show that riffles are significantly longer in some logged channels than in unlogged channels. This indicates that increased sediment loads have altered the morphology setting of these logged streams.

3.2 Pool and Riffle Spacing

The frequency distribution of pool-riffle (one pool-riffle sequence) spacing for individual unlogged and logged watershed streams is presented

in Figure A1, Appendix 1; results for channel pairs are summarized in Table 9. The conventional method of reporting spacing lengths in units of bankfull width (W_b) has been adopted here. Bankfull widths were measured in the field and were based on morphological evidence. The mean spacing for Government Creek reaches and South Bay Dump Creek range between approximately 2 W_b and 3 W_b. The spacing for reaches in Mosquito Creek is less than 2 W_b. The mean spacing in Bonanza Creek is less than in Hangover Creek.

Between-basin statistical comparisons show that there is a significant difference between spacings in two of the three unlogged-logged pairs and in the unlogged-logged and torrented basin pair (Table 9). In both the Government Creek Reach B-Mosquito Creek Main and Government Creek Reach D-Mosquito Creek Tributary pairs, the logged basin channels have shorter spacings than their corresponding unlogged basin channels. Although the spacing is shorter in SBD than in GD, the difference is not significant; the difference between SBD and MT is significant at the 95% confidence level. There is no significant difference in spacing lengths between Hangover and Bonanza creeks.

In all cases, the pool-riffle spacing lengths presented here for selected Queen Charlotte Islands streams are shorter than the commonly referenced average of 5 to 7 widths (Leopold et al. 1964). They are also shorter than reported average values of between 3 1/2 and 6 widths for coastal California channels (Keller et al. 1981).

It appears from the above results (Table 9) that pool-riffle spacing is significantly shorter in some logged channels than in the corresponding unlogged channels. However, Hogan (1985) states that this difference cannot be attributed directly to infilling of pools by increased sediment loads. His results show that the shorter pool-riffle spacing lengths may be due partially to altered LOD characteristics or may even be an artifact of the analytical procedure used. The influence of altered LOD characteristics on channel morphology is considered in Section 4. The analytical problems stem from the use of bankfull width to standardize spacing lengths. If channel widths increase, as is often the case in

TABLE 9. Pool-riffle sequence spacings[a]

	GB Not logged	MM Logged	GD Not logged	MT Logged and torrented	SBD	Hang Not logged	Ponz Logged
Pool-riffle sequence							
Mean spacing distance in bankfull widths (W_b)	2.79	1.66	2.85	1.32	2.66	3.51	2.70
Standard deviation	1.49	0.64	1.56	0.57	1.43	1.59	1.90
Difference ($\alpha = 0.05$)	SIGNIFICANT		SIGNIFICANT			NOT SIGNIFICANT	
Number of sequence	22	18	18	13	9	21	18
Mean bankfull width (m)	20.2	37.6	18.8	27.7	21.0	29.3	45.4
Survey length (m)	981	1251	575	479	471	1844	2143
Comments	Pool-riffle spacing significantly shorter in logged reach		Pool-riffle spacing significantly shorter in logged reach			Pool-riffle spacing not changed	

[a] See Figure A1 and Table A3 in Appendix 1 for complete results.

logged channels (see Section 4), standardized spacing lengths will appear shorter even without an actual change in pool-riffle proportions. Adjusting for increased channel widths appears to account for the apparent differences in spacing (Table A3 in Appendix).

3.3 Riffle Height, Relative Pool Depth, and Riffle Steepness

The vertical components of the longitudinal profile were examined in terms of riffle height, relative pool depth, and riffle steepness. Channel gradient is taken into account for calculating riffle heights. Riffle steepness is the riffle height divided by riffle length; and relative pool depth is the riffle height divided by the pool-riffle spacing length (Figure 5). Relative pool depth is used to provide a scaled measure of the infilling of pools: smaller values indicate shallower pools. Larger average riffle steepness values indicate riffles are relatively steep and suggest that they are building into the downstream pool.

The channel-averaged results are summarized and compared in Table 10; complete results are in Tables A4 and A5; Appendix 1. Riffle height is scale dependent, so that only streams of similar size can be compared. There is a significant difference ($\alpha = 0.05$) in riffle height between Government Reach B and Mosquito Main, and between Government Reach D and Mosquito Tributary. In both cases the average values are lower in the Government Creek pairs (Table 10). This indicates that bar relief is increased in the logged channels and suggests that riffles are building into the downstream pool. The differences in basin morphometry between Government and Mosquito creeks may contribute partially to this difference. There is no difference in the average riffle height between either Government Reach D and South Bay Dump or Hangover and Bonanza Creek.

In relative pool depths, however, there is a significant difference between the Government and Mosquito Creek pairs (Table 10), but the pattern is reversed in each: depths are greater in Government Reach B than in Mosquito Tributary, and greater in Mosquito Tributary than in Government Reach D (Table 10). This indicates that pools in Mosquito Main

TABLE 10. Riffle height, relative pool depth, and riffle steepness[a]

	GB Not logged	MM Logged	GD Not logged	MT Logged	SBD and torrented	Hang Not logged	Bonz logged
Avg. riffle height (m)	0.305	0.667	0.324	0.662	0.440	0.618	0.681
Difference (α = 0.05)	SIGNIFICANT		SIGNIFICANT			NOT SIGNIFICANT	
Avg. relative pool depth (m/m)	0.0163	0.0128	0.0101	0.0200	0.0112	0.0133	0.0112
Difference (α = 0.05)	SIGNIFICANT		SIGNIFICANT			NOT SIGNIFICANT	
Avg. riffle steepness (m/m)	0.0214	0.0211	0.0315	0.0295	0.0133	0.0225	0.0262
Difference (α = 0.05)	SIGNIFICANT		SIGNIFICANT			NOT SIGNIFICANT	
COMMENTS	Pools are shallow in logged reach; infilling of pools		Riffles are larger (in the vertical) in logged reaches; riffle building			No difference in the vertical dimensions of pools and riffles between reaches	

[a] See Tables A4 and A5 in Appendix 1 for complete results.

Creek have undergone some infilling, but it is not evident in Mosquito Tributary. The apparent deepening of pools in Mosquito Tributary is due to pools associated with deep scour holes around large organic debris pieces (see Section 4.2). There is no significant difference in relative pool depths between Government Reach D and South Bay Dump Creek.

In riffle steepness values there is no significant difference between any of the unlogged, logged, or torrented channel pairs. This indicates that riffle surface gradients are similar in all pairs.

Based on the longitudinal profile of the nine stream sections, it appears that a significant difference exists in riffle height and relative pool depth between older logged and unlogged basin channels. Although the greater riffle heights in the older logged area indicate that riffle steepness is increased, this generalization is not supported by the scaled measures. There is an indication that pools have been infilled in Mosquito Main, leading to reduced overwintering habitat, but this tendency is masked in Mosquito Tributary because of the influence of large organic debris.

3.4 Summary

Pools and riffles are important components of fish habitat. They are also channel features that reflect changes in sediment supply to the stream. Thus, they provide both a useful measure of habitat character and an indirect indicator of the influence of land-use practices and debris torrents on channel conditions. Longitudinal profiles are used to determine if pool-riffle spacing, riffle height, and proportions are significantly different in selected paired unlogged and logged stream channels.

Significant differences exist in several pool and riffle characteristics between unlogged, logged, and torrented channel types. Riffles are proportionally larger than pools, pool-riffle spacings are reduced, and pools are shallower in the torrented and logged channels. Although the influence of LOD and analytical limitations have complicated

the interpretation of results slightly, it appears from the channel scale data that logging and debris torrenting have altered the fluvial sediment loads, and that this has resulted in significant alterations to morphological features important to fish use.

4 REACH SCALE MORPHOLOGICAL STUDIES

Detailed morphological studies were conducted in eight stream reaches: four unlogged, three logged, and one logged and debris-torrented. Although a wide range of features was considered, the obvious and overwhelming importance of large organic debris as an independent variable influencing morphology dictated that this variable be considered initially. After LOD characteristics in the reach pairs are compared, its influence on channel morphology is evaluated.

4.1 Large Organic Debris Characteristics

The physical importance of large organic debris to stream channel morphology has received considerable attention in the literature. Studies have dealt with the influence of LOD on flow velocities and on the localized dissipation of potential energy at log steps (Heede 1972; Marston 1982), which results in reduced channel erosion and differential movement and storage of clastic sediment (Megahan and Nowlin 1976; Swanson and Lienkaemper 1978; Mosley 1981; Swanson et al. 1982; Pitlick 1982). LOD has also been shown to contribute significantly to local channel gradient and bed topography (Keller and Swanson 1979; Keller and Tally 1979; Keller et al. 1981; and Toews and Moore 1982a). This study examines and compares LOD quantities, and concentrates on its functional arrangement and resulting morphological features.

4.1.1 Large organic debris quantities

The total number of large organic debris pieces in each reach is presented in Table 11. The area of the study channel is used to standardize the data for comparison between reaches. In terms of the number of pieces per unit channel area, the paired reaches reveal no consistent pattern. There are fewer pieces in Government Reach D than in Mosquito Tributary, but the opposite pattern occurs between Mosquito Main and the other Government Creek reaches.

TABLE 11. Number of pieces and volumes of large organic debris

Stream pairs	Number of pieces	Total volume (m^3)	Study channel area (m^2)	No. per unit channel area	Volume per unit channel area (m^3/m^2)	Mean volume (m^3)	Standard deviation vol. (m^3)	Stability index[a]
GB	236	280.04	4 937.5	0.048	0.057	1.19	2.83	high
GC	204	306.89	5 268.2	0.039	0.058	1.50	4.82	high
GD	186	192.90	4 320.3	0.043	0.045	1.04	2.98	high
MH	209	286.46	10 153.7	0.021	0.028	1.37	4.52	low
MT	290	234.05	6 169.3	0.047	0.038	0.69	2.33	low
SBD	455	379.11	7 226.6	0.063	0.053	0.64	1.62	low
Hang	182	395.56	7 653.7	0.024	0.052	2.17	5.22	high
Bonz	186	537.85	13 653.7	0.014	0.039	3.09	7.08	medium

[a] Stability index: high - 50% LOD covered by moss.
medium - 20-50% LOD covered by moss.
low - 20% LOD covered by moss.

The range in LOD volumes per unit channel area (Table 11) is similar to that exhibited by the number of pieces. However, with the exception of Government Reach D and Mosquito Tributary, the mean debris loading by volume in logged (non-torrented) reaches is substantially lower than in unlogged reaches. There is approximately 15% more material by volume in the torrented South Bay Dump than in the unlogged Government Reach D.

The mean volume of individual debris pieces for each reach is also presented in Table 11. The large standard deviations indicate that the wood material consists of a wide range of sizes. If logging alters the character of woody material through both removal of large material and break-up of material into smaller pieces (Toews and Moore 1982), there should be a difference in the size distribution between reach pairs. Frequency histograms of large organic debris volumes for individual logged, unlogged, and torrented reaches are presented in Figure 8. Analysis of variance tests (Table A6 Appendix 1) indicate that the mean large organic debris volume is significantly ($\alpha = 0.5$) smaller in both Mosquito Tributary and South Bay Dump than in Government Reach D. In all cases there is a higher frequency of very small material in logged and torrented channels and more intermediate-sized material (0.13-3.0 m^3) in unlogged streams, as observed by Toews and Moore (1982) in Carnation Creek on Vancouver Island. There are relatively few very large pieces in each stream type. The intermediate- and larger-sized material will have the greatest influence on the channel character. This should depend, however, on the position of the debris with respect to the stream flow.

4.1.2 Large organic debris arrangement within the channel zone

A commonly held opinion in fish habitat rehabilitation is that "...management plans dealing with large organic debris should strive to duplicate natural processes found in undisturbed basins" (Keller et al. 1981, p. 175). Although several previous studies have provided inventories of large organic debris quantities and noted the

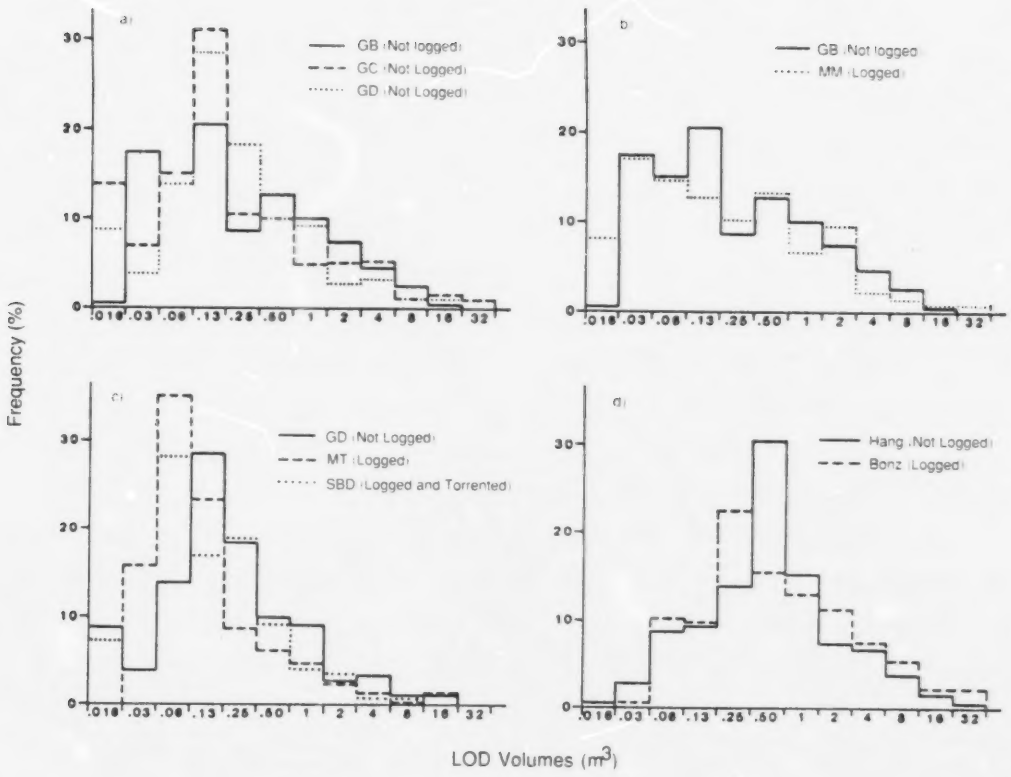


FIGURE 8. Frequency distribution of large organic debris by volumes.

influence of specific debris pieces on channel morphology, there has been relatively little work done on the actual placement or arrangement of the material within the channel zone. The orientation of material is important because specific channel features, such as pools, riffles, and gravel bars, will depend partially on the way in which woody material influences stream flow direction. Specific orientations may produce particular features; some may be preferred fish habitat. Also, documentation of debris arrangement patterns provides a basis upon which to "duplicate" undisturbed channel conditions.

Field investigations indicated that much of the stable large woody material which influences pool and riffle configuration and stored clastic sediment crosses the channel diagonally with the small diameter end of the logs pointing either up- or downstream. Cross-channel debris appears to be more prevalent in unlogged basins (Figures 9 and 10) and material oriented parallel to the channel banks appears more frequently in logged basin streams (Figures 12 and 13). This pattern is thought to be due to the generally smaller nature and greater mobility of debris in logged basin streams.

To determine whether or not a preferred orientation exists in each stream type, the orientation of each debris piece was measured on the large organic debris maps (Figures 9 to 16). All orientation measurements were made with respect to a center line drawn parallel to the trend of the channel banks; a definition sketch is provided in Figure 17. Log direction (small diameter end pointing up- or downstream) was based on log end diameter or position of the root wad. The long axes of debris clusters were measured if it was not possible to account for individual pieces.

Initially, debris arrangement depends on the mechanism of input from the overbank zone to the stream channel. The main debris input is mass-wastage from adjacent hillslopes, tree blow down, near-channel debris input by bank erosion, and flotation of woody material from upstream (Keller and Swanson 1979). All appear

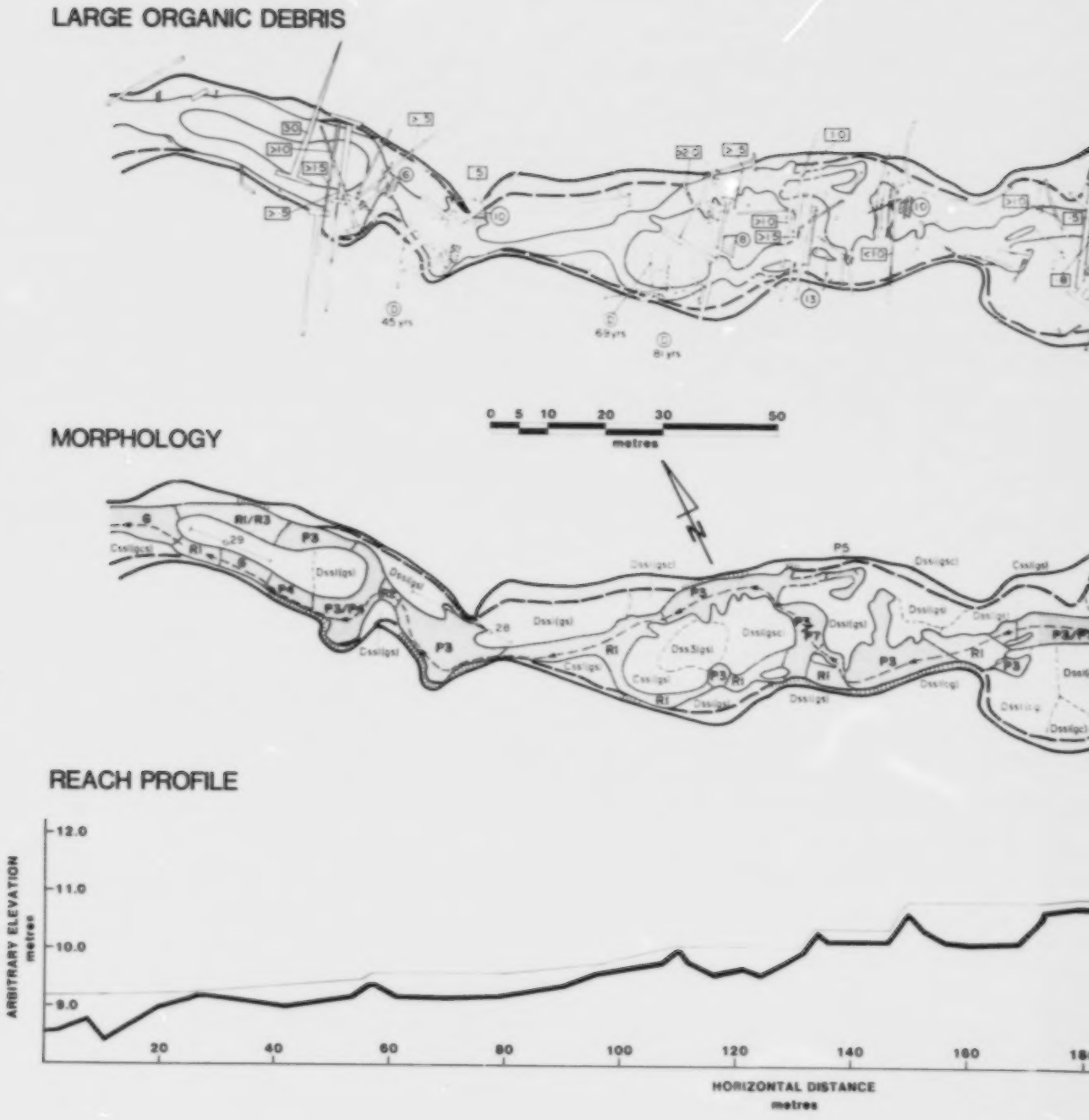


FIGURE 9. LOD, morphology, and longitudinal profile of Government Reach B.

P5
Dssl(gs)
Cssl(gs)
P5
P3
Dssl(gs)
Dssl(gs)
Dssl(gs)
Dssl(gs)
Dssl(gs)
Dssl(gs)
P3
P3/P7
P3
P3
Dssl(gs)
Dssl(cg)
Dssl(cg)
Dssl(cg)
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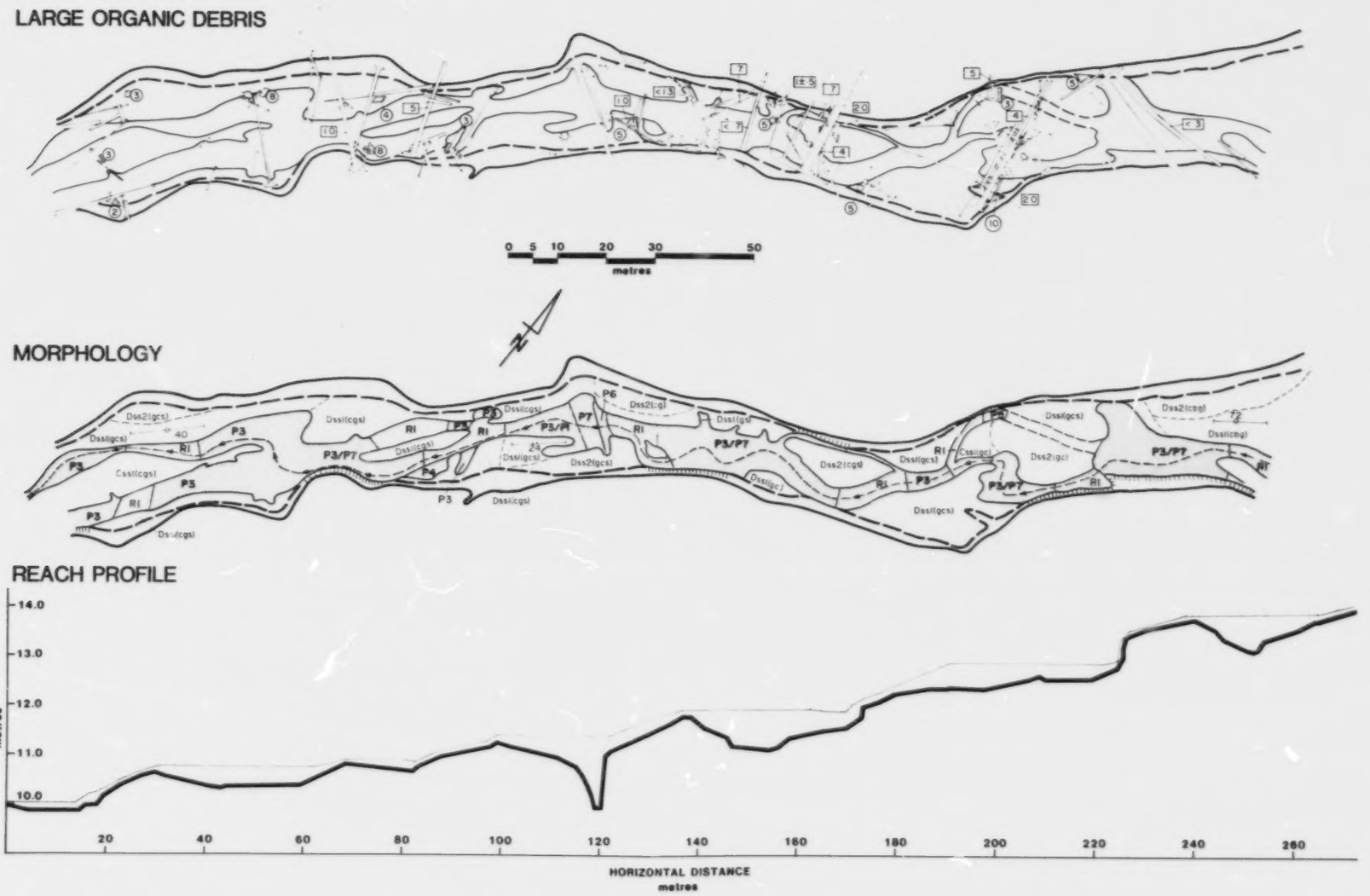
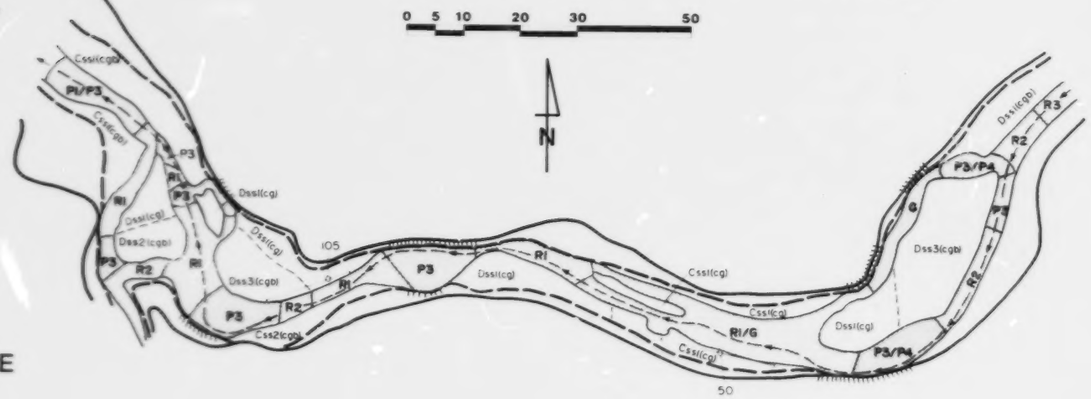


FIGURE 10. LOD, morphology, and longitudinal profile of Government Reach C.

TOP OF CHANNEL BANK
BOTTOM OF CHANNEL BANK
STREAM
BACKWATER
POOL AND RIFFLE DIVISIONS
THALWEG AND FLOW DIRECTION
UNDERCUT BANK
DEPOSITION BOUNDARY
LOD
SURFACE LOD
DATED DEBRIS: MINIMUM TIME IN CHANNEL
LOD CLUSTER
NUMBER OF PIECES IN CLUSTER
STUMP
DISTANCE FROM BOTTOM OF LOD TO WATER SURFACE
MEDIAN SEDIMENT SIZE (b-axis, mm)
LENGTH AND LOCATION OF SURFACE LINE TRANSECT
MEDIAN SEDIMENT SIZE (b-axis, mm) by Wolman Sampler
POOLS
P1: TRENCH POOL
P2: PLUNGE POOL (LOD)
P3: LATERAL SCOUR POOL (LOD)
P4: LATERAL SCOUR POOL (ROOTWAD)
P5: BACKWATER POOL (ROOTWAD)
P6: LOD DAMMED POOL
P7: UNDERSCOUR POOL (LOD)
GLIDE
G: GLIDE
RIFFLES
R1: LOW GRADIENT RIFFLE (s≤0.04)
R2: RAPIDS (s>0.04)
R3: CASCADE RIFFLE (Series of boulder steps and small ponds.)
STORED SEDIMENT
Dss: STORED CLASTIC SEDIMENT (LOD)
Css: STORED CLASTIC SEDIMENT ALONG CHANNEL ZONE, MINOR INFLUENCE OF LOD.
STABILITY
1: LOW - not vegetated, sediment moved during annual floods.
2: MODERATE - young alder and grass present, moved during large storms.
3: HIGH - old, well-established moss and trees (deciduous and conifers).
TEXTURE
b: BOULDER b-axis>256mm
c: COBBLE b-axis 64-256mm
g: GRAVEL (PEBBLE) b-axis 2-64mm
s: SAND b-axis<2mm

LARGE ORGANIC DEBRIS

MORPHOLOGY



REACH PROFILE

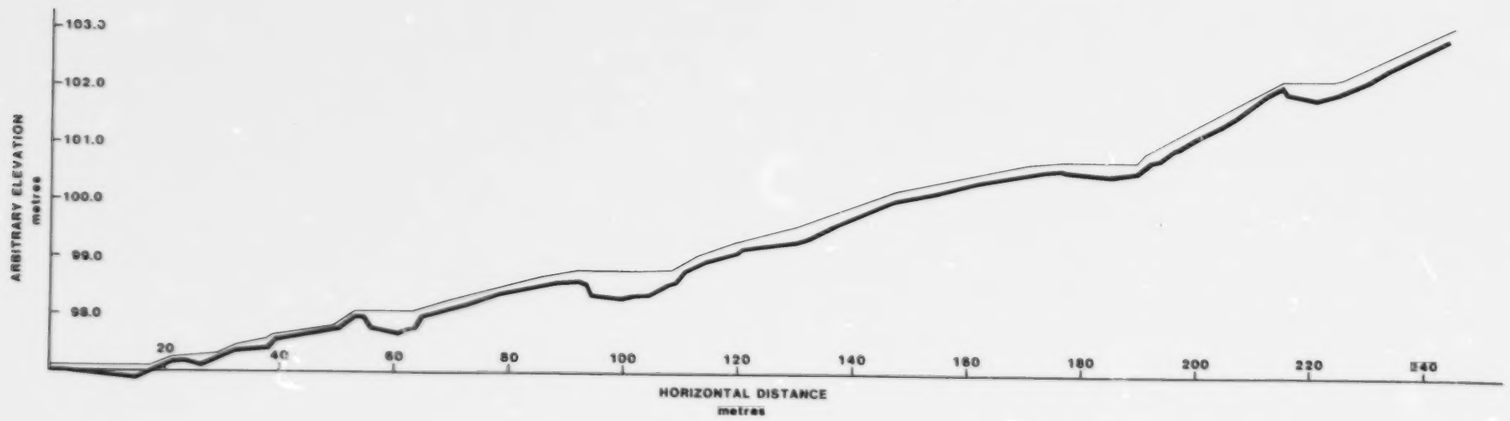


FIGURE 11. LOD, morphology, and longitudinal profile of Government Reach D.

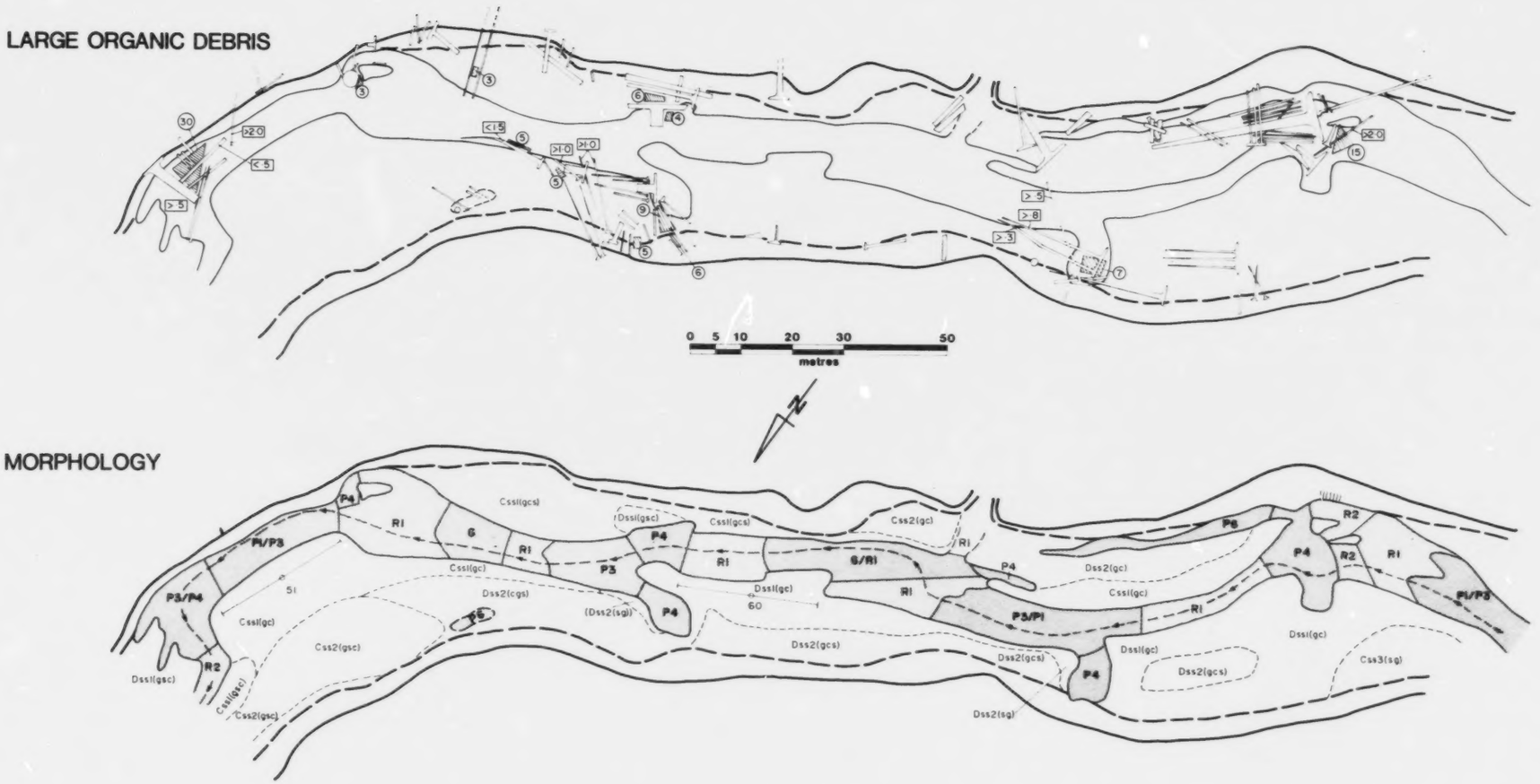
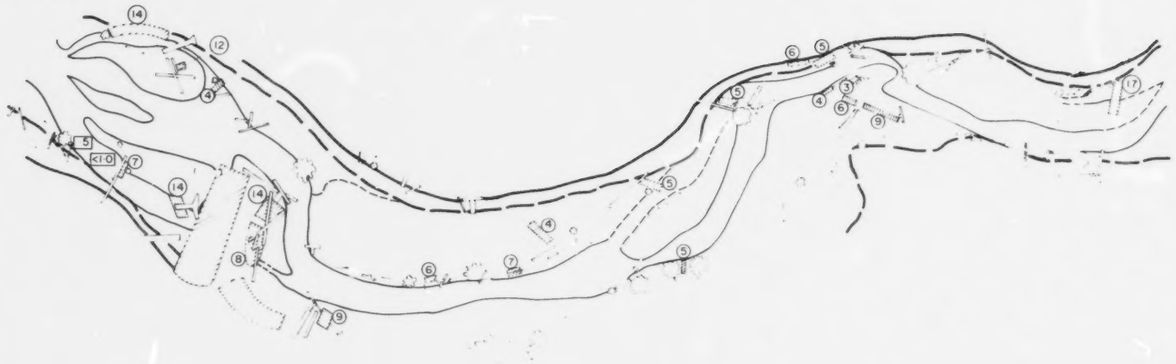


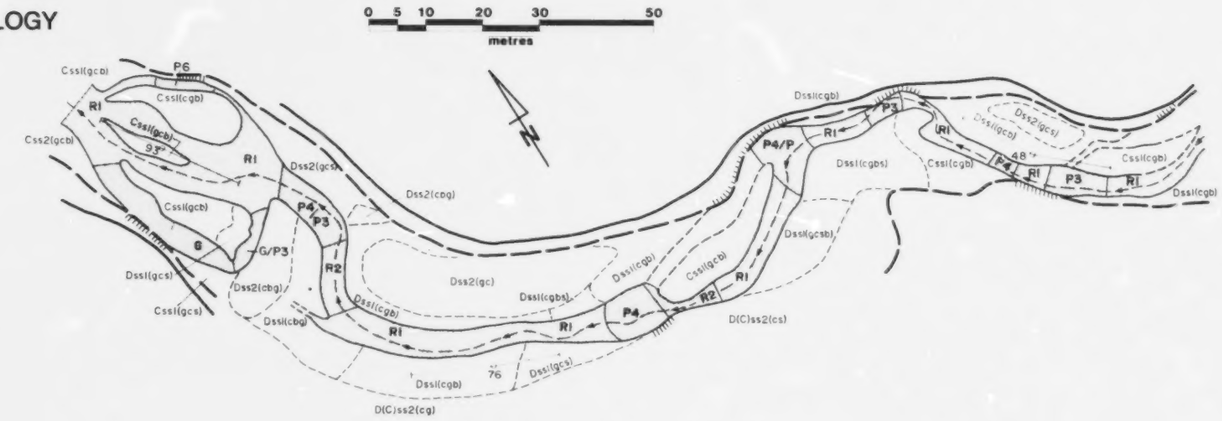
FIGURE 12. LOD, morphology, and longitudinal profile of Mosquito Main.

TOP OF CHANNEL BANK
BOTTOM OF CHANNEL BANK
STREAM
BACKWATER
POOL AND RIFFLE DIVISIONS
THALWEG AND FLOW DIRECTION
UNDERCUT BANK
DEPOSITION BOUNDARY
LOD
BURIED LOG
DATED DEBRIS, MINIMUM TIME IN CHANNEL
LOD CLUSTER
NUMBER OF PIECES IN CLUSTER
STUMP
DISTANCE FROM BOTTOM OF LOD TO WATER SURFACE
MEDIAN SEDIMENT SIZE (b-axis, mm)
LENGTH AND LOCATION OF SURFACE LINE TRANSECT
MEDIAN SEDIMENT SIZE (b-axis, mm) by McNeil Sampler
POOLS
P1: TRENCH POOL
P2: PLUNGE POOL (LOD)
P3: LATERAL SCOUR POOL (LOD)
P4: LATERAL SCOUR POOL (ROOTWADS)
P5: BACKWATER POOL (ROOTWADS)
P6: LOD DAMMED POOL
P7: UNDERSCOUR POOL (LOD)
GLIDE
G: GLIDE
RIFFLES
R1: LOW GRADIENT RIFFLE (s<0.04)
R2: RAPIDS (s>0.04)
R3: CASCADE RIFFLE (Series of boulder steps and small ponds.)
STORED SEDIMENT
Dss: STORED CLASTIC SEDIMENT (LOD)
Css: STORED CLASTIC SEDIMENT ALONG CHANNEL ZONE, MINOR INFLUENCE OF LOD.
STABILITY
1: LOW - not vegetated, sediment moved during annual floods.
2: MODERATE - young alder and grass present, moved during large storms.
3: HIGH - old, well-established moss and trees (deciduous and conifers).
TEXTURE
b: BOULDER b-axis>256mm
c: COBBLE b-axis 64-256mm
g: GRAVEL (PEBBLE) b-axis 2-64mm
s: SAND b-axis< 2mm

LARGE ORGANIC DEBRIS



MORPHOLOGY



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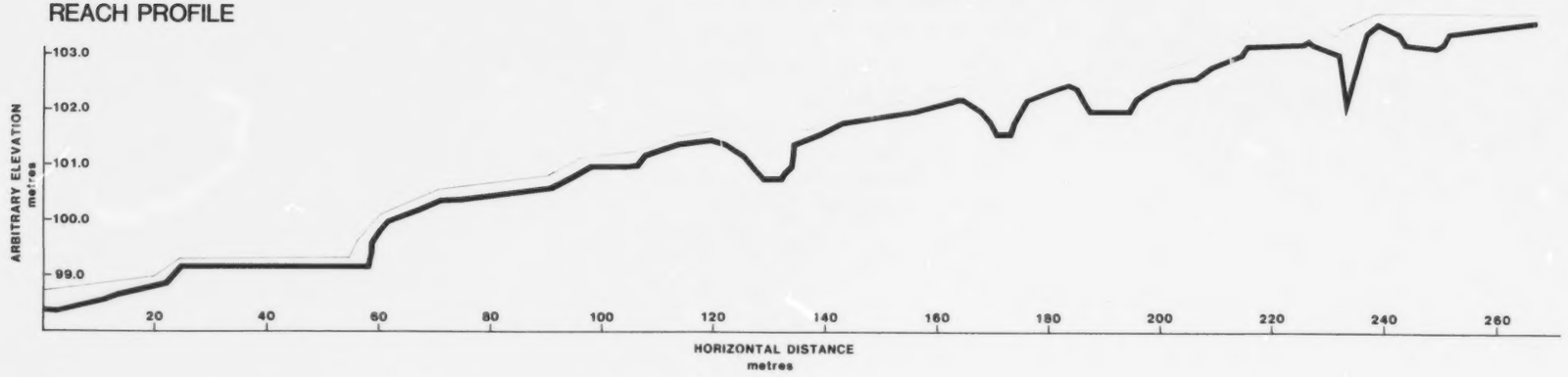


FIGURE 13. LOD, morphology, and longitudinal profile of Mosquito Tributary.

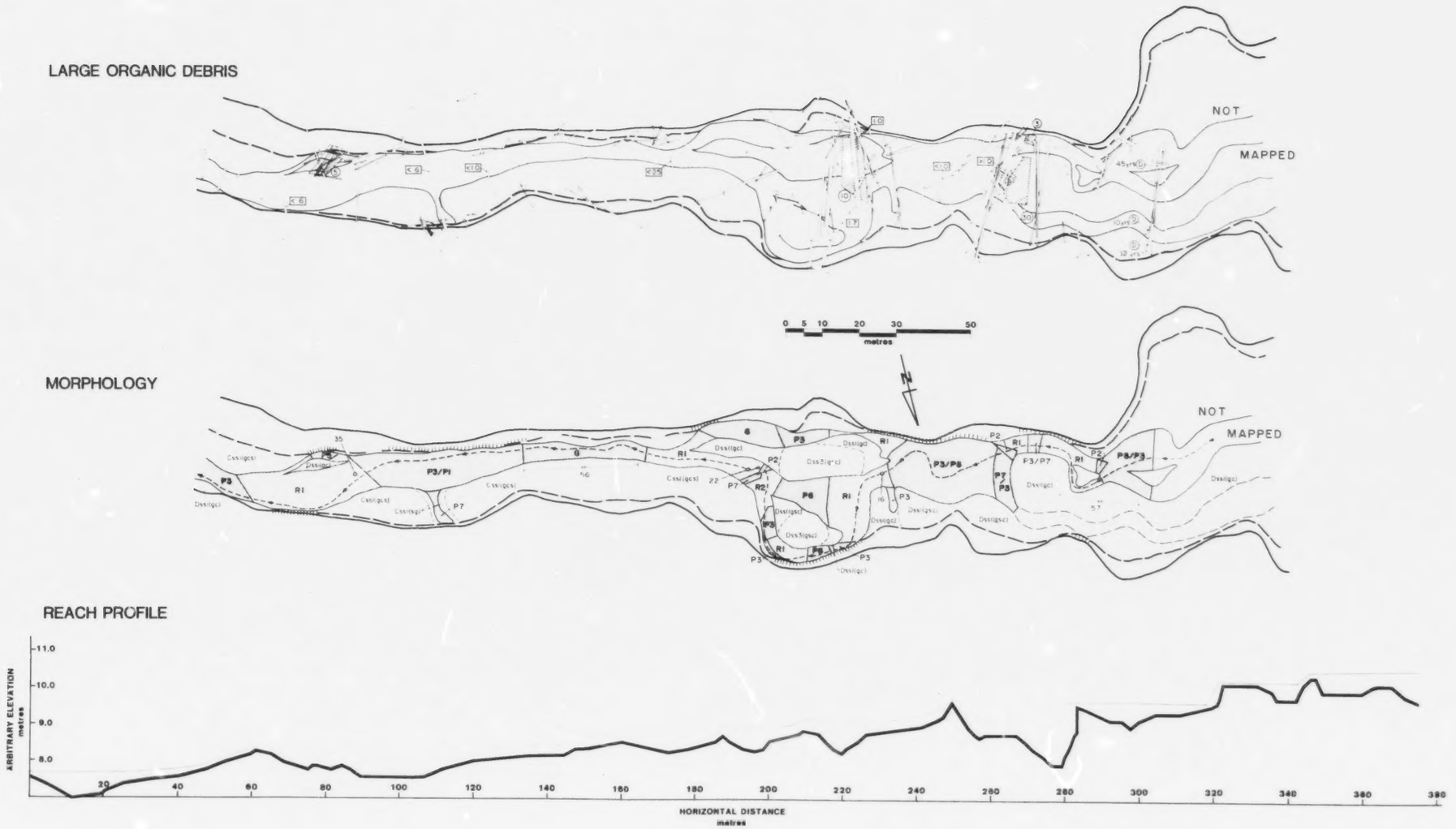
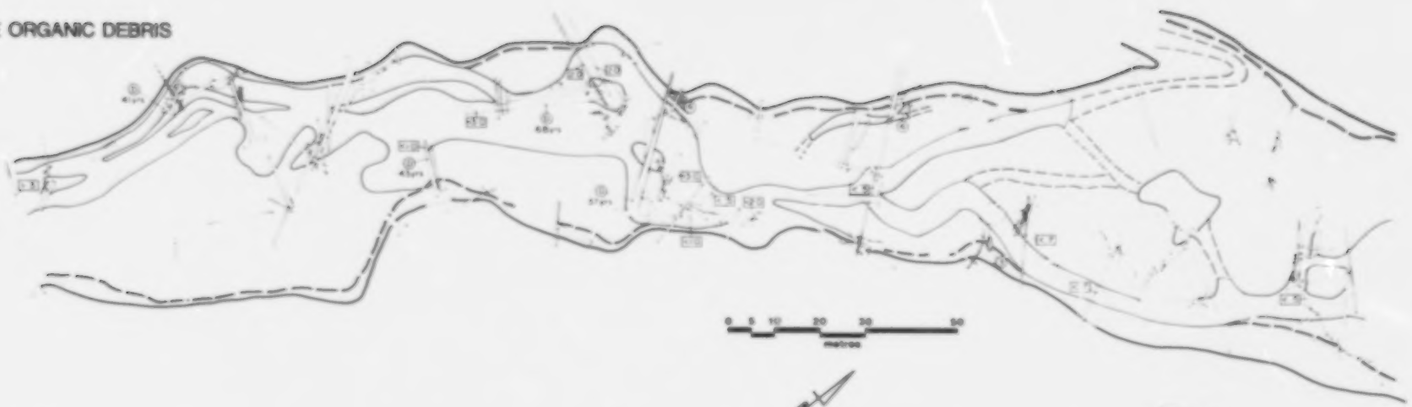
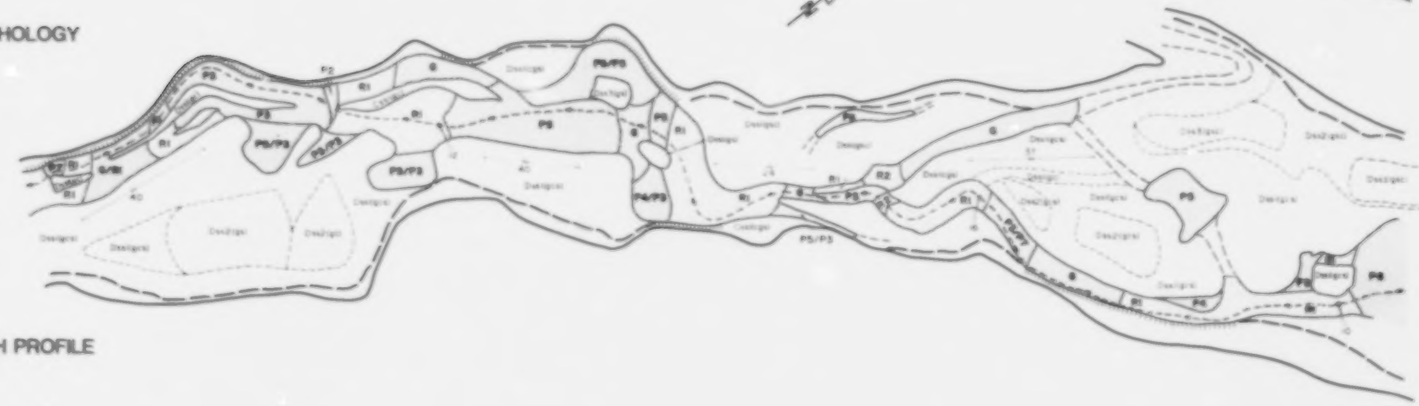


FIGURE 14. LOD, morphology, and longitudinal profile of Hangover Creek.

LARGE ORGANIC DEBRIS



MORPHOLOGY



REACH PROFILE

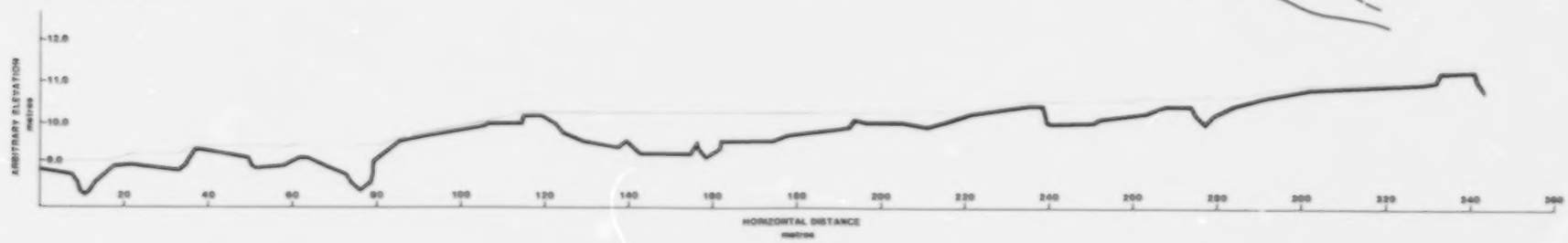


FIGURE 15. LOD, morphology, and longitudinal profile of Bonanza Creek.

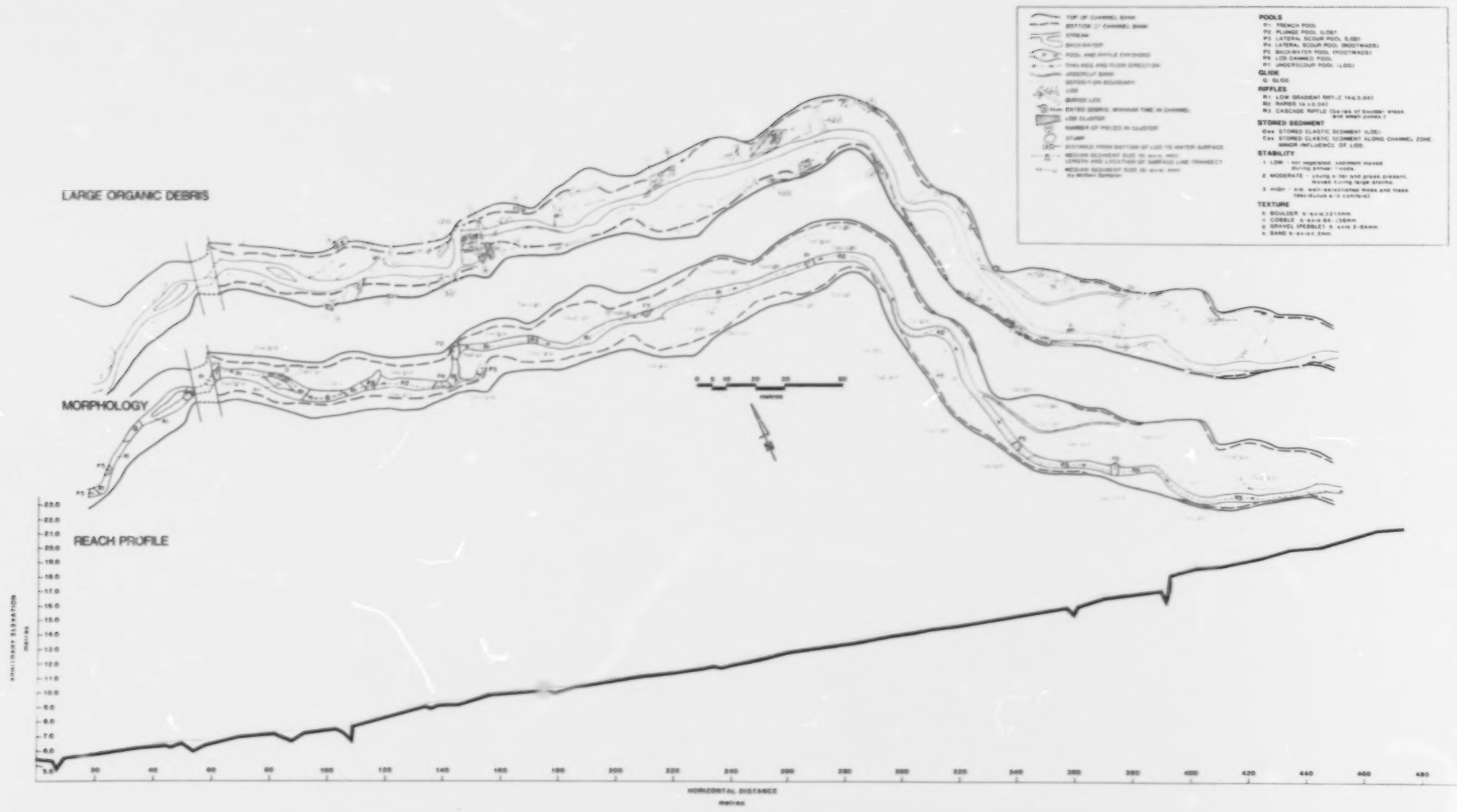
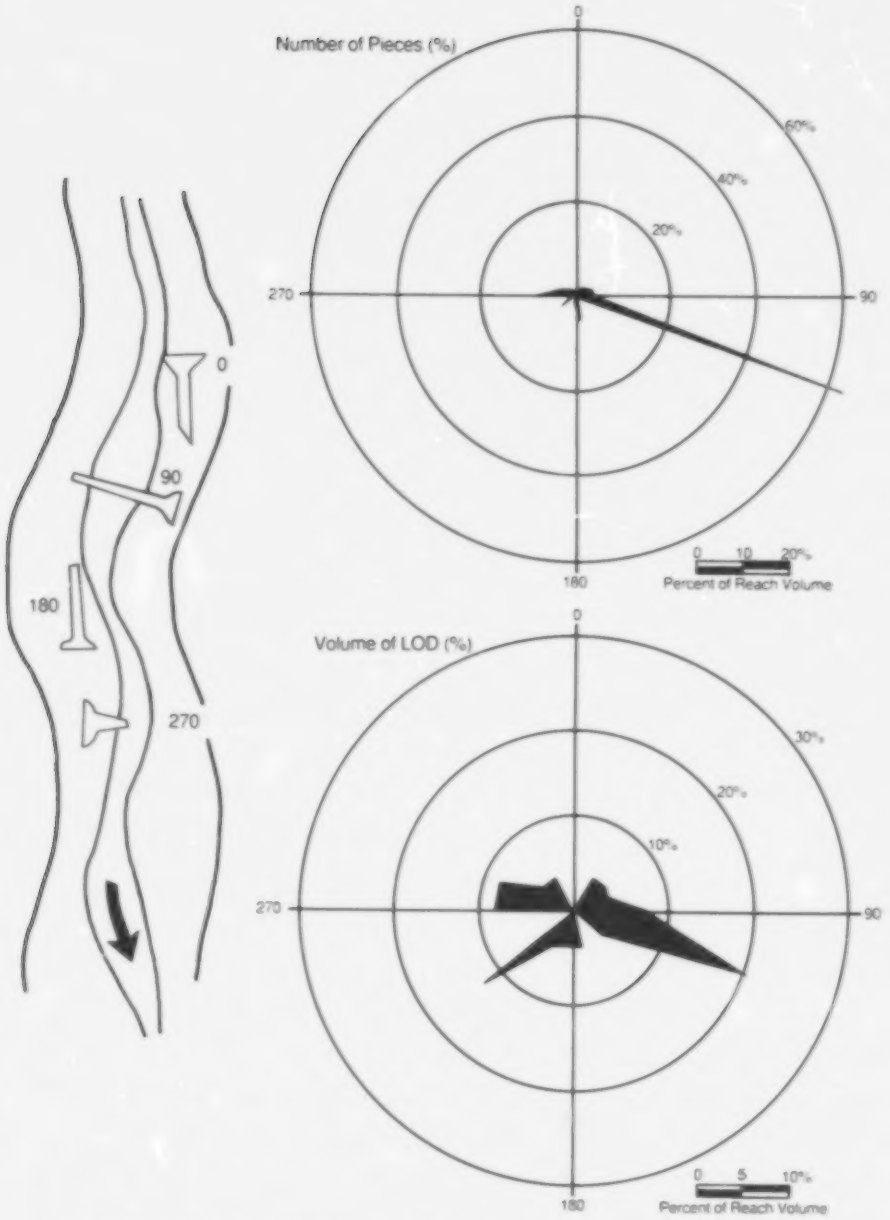

LARGE ORGANIC DEBRIS
MORPHOLOGY
REACH PROFILE
POOLS
P1: TRENCH POOL
P2: PLUNGE POOL (LOD)
P3: LATERAL SCOUR POOL (LOD)
P4: LATERAL SCOUR POOL (ROOTWADS)
P5: BACKWATER POOL (ROOTWADS)
P6: LOD DAMMED POOL
P7: UNDERSCOUR POOL (LOD)
GLIDE
G: GLIDE
RIFFLES
R1: LOW GRADIENT RIFFLE (s≤0.04)
R2: RAPIDS (s >0.04)
R3: CASCADE RIFFLE (Series of boulder steps and small ponds.)
STORED SEDIMENT
Dbs: STORED CLASTIC SEDIMENT (LOD)
Cas: STORED CLASTIC SEDIMENT ALONG CHANNEL ZONE OF MINOR INFLUENCE OF LOD.
STABILITY
1: LOW - non vegetated sediment moved during annual flows.
2: MODERATE - young alder and grass present, moved during large storms.
3: HIGH - old, well-established mosses and trees (dbh>bulb e.g. contains)
TEXTURE
b: BOULDER b-axis>256mm
c: COBBLE b-axis 64 - 256mm
g: GRAVEL (PEBBLE) b-axis 2-64mm
s: SAND b-axis< 2mm
HORIZONTAL DISTANCE
metres

FIGURE 16. LOD, morphology, and longitudinal profile of South Bay Dump Creek.



LOD is Defined as all In Channel Woody Material With Diameters Greater Than 0.1m and Lengths Exceeding 3.0m
Long Axis Orientation of I.. stream LOD by Volume

FIGURE 17. Orientation of LOD by volume prior to rearrangement by streamflow.

to be important in the streams studied, although direct mass wastage was evident in South Bay Dump only. The orientation of material entering the stream system by all mechanisms other than flotation was determined by considering only material more than 1 m above the channel surface (in all cases this debris is not influenced by flood flows). The number of pieces and volume of large organic debris contained within 20° sectors (plotted as interval mid-points) for all material more than 1 m above the channel is presented in Figure 17. It is evident that the most prevalent orientation of material prior to rearrangement by streamflow is diagonally across the channel. The most frequent orientation sector is between 100-120° and 241-280°.

However, once the material has entered the stream system and is moved during high flow events, there may be a preferred arrangement along the channel. The volume of large organic debris (excluding material greater than 1 m above the channel surface) contained within 20° sectors for each reach is presented in Figure 18. It is evident that no strongly consistent pattern emerges when only unlogged channels in Government Creek are considered (Figure 18). In general the distribution indicates that maximum volumes occur in sectors between 80-160° and 221-281°. The preferred orientation is debris placed diagonally across the channel, from either right or left bank, with the large end of the tree on the downstream end and close to the bank.

In the logged, unlogged, and torrented pairs (Figure 18), there is a definite shift in preferred orientation from the diagonal in the unlogged, toward parallel in the logged and/or torrented streams. The relatively high volumes (approximately 45% of the total material) arranged between 320 and 40° in Mosquito Main and Tributary Creeks indicate that much of the material is oriented with the large end upstream. The large value (24%) for the 80-100° sector in Mosquito Tributary is associated with one major log jam.

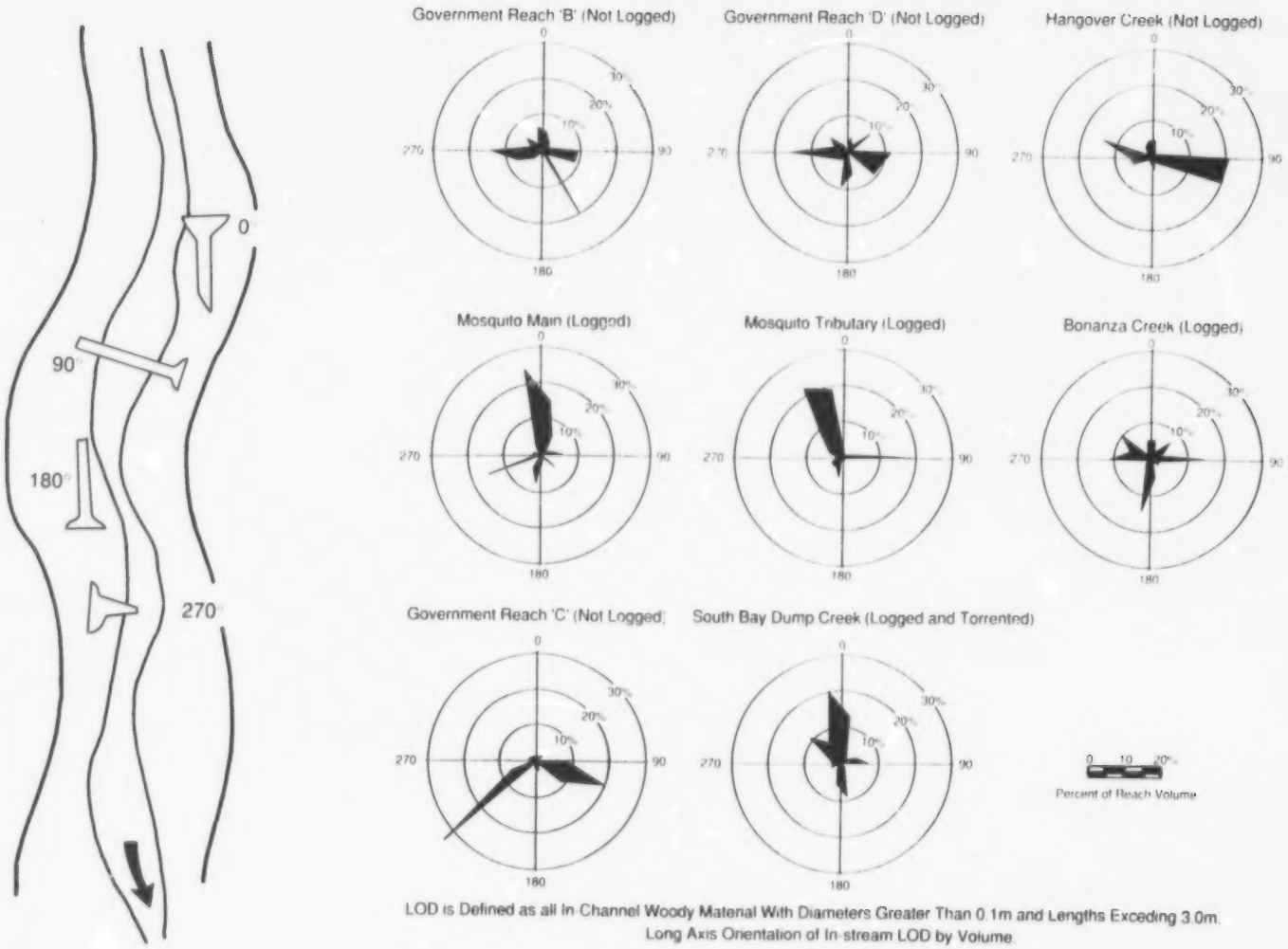


FIGURE 18. Long axis orientation of in-stream LOD by volume.

The debris distributions by orientation sector for Hangover and Bonanza creeks are similar (Figure 18d). The main departure in orientation is an increased amount lying parallel to the channel, with the large end downstream in Bonanza. Generally, both streams have a pattern similar to that of Government Creek. The similarity in LOD orientation of the logged Bonanza reach is probably due to the abundant large material remaining in the system and the continued source of large volume debris from forested stream bank areas (a leave strip was provided).

Chi-square tests on the number of LOD pieces in each sector show that a significant difference exists in the distribution between all unlogged, logged, and debris-torrented pairs. The distributions based on the number of pieces are similar to distributions by volume, except that a disproportionately few pieces comprise a large volume in some sectors, particularly 340-360°, in the logged stream type.

4.2 The Influence of Large Organic Debris on Channel Morphology

Large organic debris can be shown to influence several channel features. A prerequisite to habitat rehabilitation in general is a clear understanding of both the form and function of LOD. Its effect on channel depth, width, gradient, sediment texture and stored volumes, and pool-riffle characteristics are considered here.

4.2.1 Channel depth and width

Keller and Tally (1978) suggested that one role of large organic debris is to increase the variability in channel depths and widths. The variation of both in each study reach is shown in Figures 9-16. The influence of LOD on depth was assessed by comparing the longitudinal profiles to LOD maps, and on width by comparing the morphology to LOD maps.

Because it has two distinct sections, Hangover Creek (Figure 14) provides a clear illustration of the influence of LOD: the downstream half of the reach has below-normal debris loading, while the upstream

half has above-average quantities (Figure 14c). The longitudinal profile (Figure 14c) shows the downstream section as one long deep pool (2.5 widths in length), whereas the upstream section alternates between short pools and riffles (combined total equalling less than 1 width). While the channel width is relatively constant in the downstream section, the mean width varies by almost 30% in the upstream zone. The width doubles in certain areas with large amounts of material.

The same general pattern of low variability in zones characterized by low volumes of debris is evident in all three unlogged study reaches in Government Creek. In the two logged reaches of Mosquito Creek and in the torrented South Bay Dump Reach, the longitudinal profiles and morphological maps (Figures 12, 13, and 16) show much less depth and width variability.

The maps and longitudinal profiles show the change in bed topography and channel width associated with large organic debris. To assess the variability of depth, the standard deviation of the difference between the actual and average thalweg elevation for each partial length of channel was calculated (see definition diagram, Figure 19). The average elevation was calculated by linear regression analysis (average elevation is a function of the channel slope and distance upstream). The results are plotted with LOD relative abundance values in Figure 20. The positive depth variability values indicate that the channel bed is more irregular than the average, and the minus values indicate smooth surfaces (either riffle or pool). Therefore, a stream bed with numerous pools and riffles per unit length of channel would have a larger positive value than a similar length consisting of one pool and riffle sequence. The estimate of width variability used is the difference between the mean width for each unit length of reach (equal to one bankfull width) and reach-averaged width (Figure 19). The reach-averaged width is the area of the channel divided by reach length. Width and LOD variability are plotted together in Figure 20.

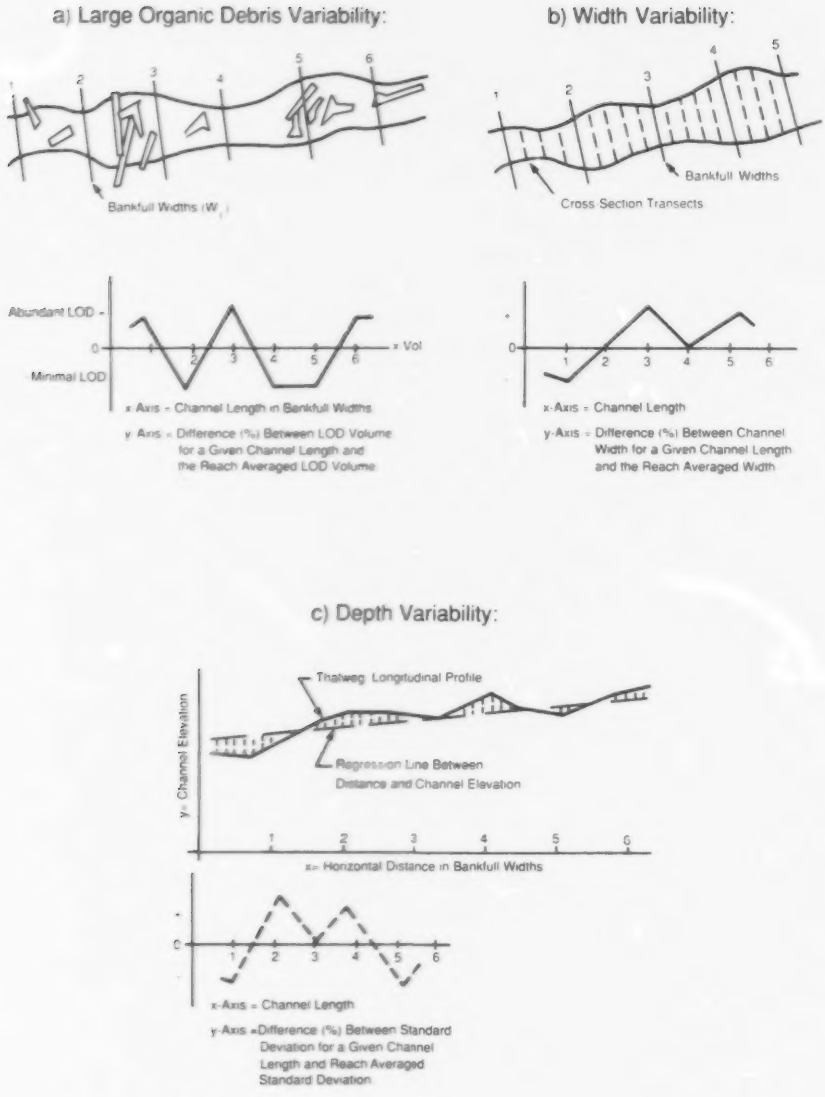

a) Large Organic Debris Variability:
Bankfull Widths (W_{bf})
Abundant LOD
Minimal LOD
x Vol
x Axis = Channel Length in Bankfull Widths
y Axis = Difference (%) Between LOD Volume for a Given Channel Length and the Reach Averaged LOD Volume
b) Width Variability:
Bankfull Widths
Cross Section Transects
x-Axis = Channel Length
y-Axis = Difference (%) Between Channel Width for a Given Channel Length and the Reach Averaged Width
c) Depth Variability:
Thalweg Longitudinal Profile
Regression Line Between Distance and Channel Elevation
y= Channel Elevation
x= Horizontal Distance in Bankfull Widths
x-Axis = Channel Length
y-Axis =Difference (%) Between Standard Deviation for a Given Channel Length and Reach Averaged Standard Deviation

FIGURE 19. Definition diagram for variability of large organic debris volumes, channel widths, and depths.

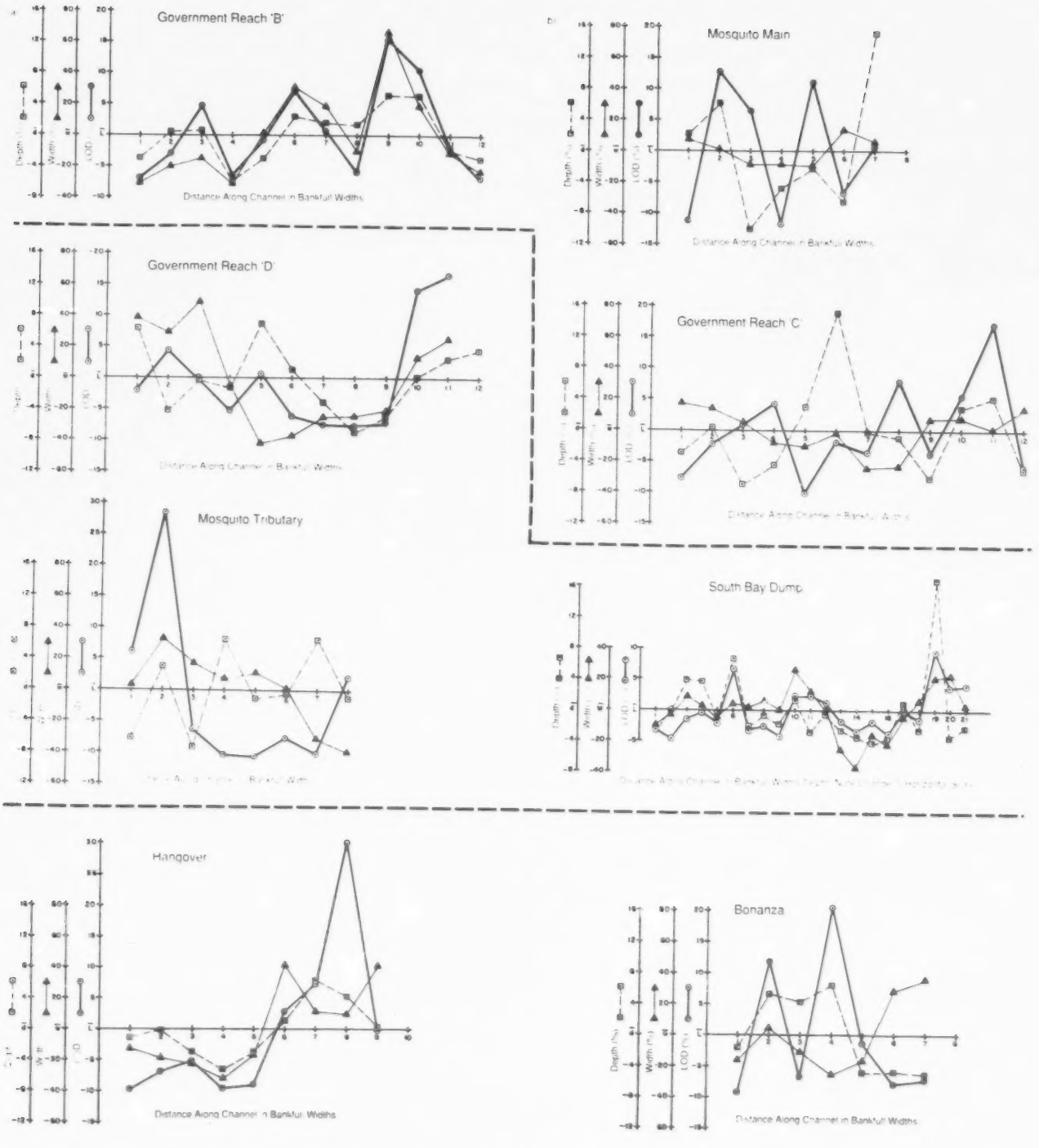


FIGURE 20. Variability of channel depth, width, and large organic debris.

The general pattern evident in Figure 20 is for both depth and width variability to increase with an increase in LOD abundance. Although the pattern is fairly consistent in Government reaches B and D and in Hangover, the relation is significant at the 95% confidence limit for the Government Reach B and South Bay Dump only (Table 12a).

The lack of high positive correlation coefficients for Government Reach C and Mosquito Main and Mosquito Tributary suggests that other factors besides LOD abundance exert an important influence over depth and width variability. Comparison of Figures 9 through 16 with Figure 20 shows that much of the departure between LOD abundance and channel width and depth trends appears to be associated with LOD orientation. The large separation between depth variability and LOD abundance at a distance of 6 widths in Government Reach C (Figure 20a) is due to a very deep but short scour pool beneath one piece of debris, which diagonally crosses the channel and is securely imbedded in both banks (Figure 10). Several other examples of this pattern of high depth and width variability values associated with normal or below-average LOD amounts are invariably related to diagonally oriented material (e.g., Mosquito Main and Mosquito Tributary; Figures 12, 13, and 20a and 20b).

In the opposite situation, where low depth and width variability values correspond to high values of LOD abundance, the channel zones are characterized by debris oriented predominantly parallel to the channel (e.g., Bonanza, Mosquito Main, and Mosquito Tributary; Figures 12, 13, 15, and 20a, b and c).

To evaluate the influence of LOD orientation on channel character, the volume of individual debris pieces in each unit length of channel was adjusted by its angle to the flow direction (see Table 12 for details). Correlation coefficients relating LOD orientation to channel depth and width variability are summarized in Table 12b. Although the relations are stronger overall, they remain -- with the exception of Government Reach B and South Bay Dump -- insignificant at the 95% confidence level. Because the study

TABLE 12. Summary of the correlation between large organic debris characteristics and channel width and depth variability

A. LOD abundance versus channel width and depth variability

Study reach pairs	Correlation coefficients (r) (product - moment)		N	$r_{c(0.05)}$	Significance[a] of relation
	LOD abundance versus: Depth variability	Width variability			
QB	0.80	0.88	12	0.58	S
QC	-0.18	-0.11	12	0.58	NS
QD	0.51	0.50	11	0.60	NS
MM	0.16	0.11	7	0.75	NS
MT	0.0	0.42	8	0.71	NS
SBD	0.67	0.60	21	0.43	S
Hang	0.76	0.47	9	0.63	S/NS
Bonz	0.74	-0.42	7	0.75	S/NS

B. LOD orientation[b] versus channel width and depth variability

QB	0.85	0.78	12	0.58	S
QC	0.22	- .05	12	0.58	NS
QD	0.43	.45	11	0.60	NS
MM	0.16	0.11	7	0.75	NS
MT	0.0	0.66	8	0.71	NS
SBD	0.81	0.46	21	0.43	S
Hang	0.76	0.55	9	0.67	S/NS
Bonz	0.73	-0.19	7	0.75	S/NS

[a] Tests if a significant relation exists between the independent variable (LOD abundance or orientation) and the dependent variables (channel depth and width); S = significant relation (α = 0.05); NS = non-significant relation (α = .05).

[b] LOD orientation refers to the angle of LOD pieces with respect to stream flow direction and is calculated as $\sum_{i=1}^{n} V \sin \theta$; where V = volume of each LOD piece, θ = angle of LOD piece, n = number of pieces in each unit length.

N = Number of unit lengths (bankfull widths) used in correlation analysis.

r_c = critical values of r at probability level of 95%.

lengths are relatively short, the placement of unit lengths may influence the results.

It appears, therefore, that both LOD quantities and orientation influence channel shape, although the effects are difficult to assess statistically. In situations with abundant LOD and diagonally crossing material there is increased local bank erosion and lateral scour of the bed. In the logged and torrented channels where debris is oriented predominantly parallel to the channel, both width and depth are more consistent. Large pieces of debris lying parallel to the channel often protect the channel walls and are occasionally incorporated into the bank (e.g., upstream end of Mosquito Tributary, Figure 13). More work, particularly over longer lengths of channel, is required to determine conclusively the level of importance to be attributed to large organic debris.

Both study reaches in Mosquito Creek, as well as the South Bay Dump reach have experienced overall channel widening since logging or torrenting. Channel widths now appear to be narrowing as shown by vegetated gravel deposits (Figures 12, 13, and 16). A consequence for fish habitat of the altered channel width is the loss of undercut bank areas. A summary of cut bank areas for all study reaches is given in Table 13. It appears that channel widening was accompanied by a decrease in the area characterized by undercut banks. Both the area and volume of cut banks is much less (<5%) in Mosquito Main compared to Government Reach B. The area of overhang in Mosquito Tributary is 85% of that of Government Reach D; South Bay Dump has only 20% that of Government Reach D. The pattern is reversed in the Hangover and Bonanza creeks pair, where the former has only 80% of the area of undercut compared to the latter reach. Statistical testing is not possible because there are insufficient data to calculate the within-reach variance in the Mosquito Creek streams.

TABLE 13. Summary of channel cutbanks

Stream reach pairs	Area of overhang[a] (area/30-m channel; m^2/30 m)	Volume of overhang and undercut[b] (volume/30-m channel; m^3/30 m)	Length of study reach (m)
GB	6.23	3.20	255
GC	3.51	1.63	261
GD	5.40	2.88	216
MM	0.26	0.13	291
MT	4.60	1.42	209
SBD	0.95	1.43	420
Hang	8.16	5.10	345
Bonz	10.37	5.44	324

[a] Area of overhang is calculated as the product of the overhang width and the longitudinal length of undercut.

[b] Volume of overhang and undercut is calculated as the product of overhang width, undercut height (i.e., distance from overhang lip to the channel bed), and the longitudinal length of undercut.

4.2.2 Pool and riffle characteristics

The types and configuration of pools and riffles are presented in Figures 9-16. The classification of pool and riffle types is based on the scheme developed for fisheries studies by Bisson et al. (1982). Slight modifications were adopted; for instance, a pool formed by scour under a debris piece (P7) was added. Although the general pool and riffle breaks were accurately surveyed in the field, the delineation of specific pool and riffle types (e.g., back channel pool) was in part made afterwards with the aid of photographs and field notes. Therefore, although the boundaries are not exactly placed, the general morphological nature of each reach has been characterized.

The proportion of the total channel area of each morphological type is included in Table 14. These area values are stream flow stage dependent, hence it is difficult to compare reaches. However, the comparison of the type of feature most prevalent in each reach is appropriate. The unlogged channels are characterized by relatively more lateral scour pools (P3) and low gradient diagonal riffles (R1). Generally, in the logged channels there is an increase in the relative importance of scour pools associated with root wads (P4). Also, there are more trench pools (P1) in Mosquito Main and side channel pools (P5) in Bonanza Creek. The shift towards pools associated with root wads is due to debris oriented parallel to the channel, with the attached root wad oriented perpendicular to the flow direction (see, for example Mosquito Main, Figure 12). This debris, which is typically a large root wad attached to a short stump (cut during logging), entered the channel zone as a result of bank erosion and channel widening. The pool is a scour hole around the wad and constitutes a small break in the riffle (small pool surrounded by long riffle). This type of pool is the most frequently occurring in Mosquito Tributary (Figure 13) and provides the only deep zones in the thalweg profile. Trench pools are more abundant in areas with minimal large organic debris (Figure 11 and 12). Low-gradient riffles (R1) predominate in the logged channels and torrented reach.

TABLE 14. Area and shape[a] of pools and riffles

Stream pair	QB	QC	QD	MM	MT	SBD	Hang	Bonz
			Total area of morphological type (%)					
Morphology[b]								
P1			6.3	12.6		0.3		
P2						1.5	0.8	0.5
P3	61.9	72.8	29.3	21.7	4.5	5.7	39.5	23.2
P4		1.1		14.5	15.9	0.9		2.9
P5	1.3	0.5					0.5	16.7
P6		1.0					1.2	0.4
P7		2.5					1.2	0.4
G	6.0		4.5	13.3	9.4	6.0	9.8	16.0
R1	30.2	22.1	47.3	29.4	63.8	41.8	37.7	32.3
R2	0.8		12.6	4.9	5.5	28.6	2.2	1.8
R3						15.3		
Summary								
Pool	63.1	77.9	35.6	52.4	21.4	8.4	53.0	49.9
Glide	6.0	0	4.5	13.3	9.4	6.0	9.8	16.0
Riffle	30.9	22.1	60.0	34.3	69.3	85.6	37.0	34.1
			Mean shape index[a]					
P1			0.25	0.29		0.67		
P2						1.48	1.75	3.22
P3	0.45	0.46	0.56	0.42	0.42	0.96	0.89	1.12
P4		0.37		0.77	0.70	0.42		0.70
P5	0.44	0.39					0.30	0.72
P6		5.39		0.14	0.15		0.52	1.60
P7		9.14					5.45	0.79
G	0.41		0.10	0.50	1.59	0.42	0.22	0.47
R1	0.52	0.33	0.38	1.42	0.27	0.25	0.39	0.33
R2	0.84		0.52	0.73	0.34	0.10	0.50	0.76
R3						0.06		

[a] Shape index = $\frac{\text{area of morphological feature}}{(\text{maximum length of feature (in downstream direction)})^2} = \frac{A}{L^2}$

If shape index = 1; feature with equilateral sides
If shape index = <1; feature is long and narrow
If shape index = >1; feature is short and wide

[b] Pools, riffles, and glides are described in Figures 9-16.

Steeper riffles are also important in the South Bay Dump Creek reach (Figure 16).

The proportion of combined pools, glides, and riffles is presented in Table 14. Ignoring the problem of comparable flow-stage, and assuming that all mapping was done at "low-flow" conditions, it appears that pool type morphology is more common in unlogged reaches and glide and riffle morphology is more prevalent in logged basin channels. Riffles dominate the torrented channel. These results support the conclusions presented in Section 3 (channel scale studies).

To determine the shape of each morphological feature, a shape index was calculated and tabulated (Table 14). Because the shape index quantifies the nature of pools and riffles associated with specific channel objects (such as logs and root wads), this information is valuable for planning rehabilitation structures. Several of the mean shape index values listed in Table 14 are not good averages because an insufficient number of features was measured. The features with low area values are not properly represented by the mean shape index.

In general, the range of shape index values for the lateral scour pools (0.42-0.58) is relatively low for all Government and Mosquito Creek reaches. The morphological maps show that this pool type is proportionally longer than wide. The lateral scour pools are relatively short in Hangover, Bonanza, and South Bay Dump creeks. This is due to several small, wide pools associated with debris diagonally crossing the channel. The pools in Mosquito Main and Tributary associated with scour around root wads are wide and short (Figures 12 and 13) with shape index values of 0.77 and 0.70, respectively. Trench pools, which are not influenced by large organic debris, are considerably longer than wide, as seen in Government Reach D (shape index of 0.25) and Mosquito Main (shape index of 0.29).

The shape of the low-gradient riffles is variable (Table 14). South Bay Dump and Mosquito Tributary have the longest riffles (with

a mean shape index equal to 0.25 and 0.27, respectively, and a range of 0.10 to 0.57) and Mosquito Main has the shortest riffles (with a mean index equal to 1.42 and a range of 0.17-3.77). High-gradient riffles tend to be very long and narrow. There is a tendency for riffles to be located in areas characterized by low volumes of large organic debris. This suggests that much of the organic debris is transported over the riffle during high flow events and deposited downstream. Scour beneath and around the debris occurs, producing pools at both high and moderate flows. Riffles, therefore, are located on both the upstream and downstream end of zones characterized by abundant large organic debris volumes. Examples of this are seen in all of the reach morphology maps.

In general, the size and shape of pools and riffles has been altered in response to changed LOD characteristics. The area of pool is reduced and pool shape is changed from long and narrow in unlogged reaches to short and wide in logged and torrented areas. This appears to be due to a shift in both the debris size distribution and orientation. Riffles are frequently longer in the logged and torrented reaches than in unlogged reaches. This is in agreement with the channel scale results.

4.2.3 Sediment texture

The texture of clastic sediment in proximity to large organic debris was not rigorously measured. A qualitative assessment based on the morphology maps (Figures 9-16) is presented here (results from textural analysis of surface, subsurface, and McNeil samples, summarized on the morphological maps, are detailed in Table A7 Appendix 1). The size distributions indicate that the sediments are well sorted. The clasts are sub-angular to rounded.

The general pattern of sediment texture is characterized by relatively coarse material immediately upstream of large accumulations of debris, with a tail of fine-textured material extending downstream. Government Creek Reach C provides an example

of this pattern. At the upstream end of this reach, and upstream of the large diagonally crossing debris, cobble-size sediment (median b-axis length equal to 72 mm) predominates. Downstream of the debris the sediment texture is finer, consisting primarily of gravel. Also in Government Reach C, the large debris step (approximately 1 m high at the downstream end of the reach; see Figure 6) influences sediment texture. The material deposited in mid-channel upstream of the LOD step is considerably coarser than the sediment found further upstream (40 mm opposed to 24 mm upstream). Additional examples of this general pattern are seen in Government Reach D at 40 m upstream from the reach beginning. In this case, relatively stable cobbles, gravel, and boulders prevail upstream of the debris, while only cobbles and gravel occur downstream. Hangover has several similar examples: at the first major debris accumulation (200 m upstream, Figure 14) gravel- and cobble-sized sediment are most abundant upstream, while gravel, sand, and cobble textures extend downstream.

A similar pattern exists in the logged study reaches whenever LOD is oriented across the channel such that stream flow direction is altered. However, debris in this arrangement occurs less frequently in logged channels; hence, the sediment texture pattern is less variable.

The sediment texture of South Bay Dump Creek also displays little variability (Figure 16). Areas of relatively coarse material are found locally in steep areas and where the channel is incised. Above the large debris step (at 390 m, Figure 16) the channel bed is characterized by imbricated boulders. During flood flows, sediment is transported over the step -- or under it if the main debris piece is dislodged -- and deposited downstream. If the flows disturb the coarse layer of surface sediment, the finer subsurface material is accessible. This material is transported and deposited downstream, leading to the finer-textured sediment typical in zones of aggradation (e.g., at 290 m, Figure 16).

4.2.4 Channel gradient and stored sediment volumes

In all of the streams studied, large organic debris exerts considerable control over the longitudinal profile by: 1) causing a stepped bed profile; 2) altering sediment storage characteristics; and 3) influencing channel stability. To evaluate these features it is necessary to re-examine the channel scale longitudinal profiles presented in Section 3, as well as the detailed study reaches.

It is evident (Figures 6 and 7) that debris steps (defined as LOD pieces which cross the channel and alter both the water surface and bed elevation) exert a considerable influence on the channel gradient locally. In Government Creek, LOD steps account for between 6.7 and 13.4% of the total drop in bed elevation (Table 15). Large organic debris steps are not present in either of the surveyed channels in Mosquito Creek. Debris steps account for 7.3% of the total change in South Bay Dump. The longitudinal profiles also show that quantities of stored sediment occur immediately upstream of debris steps. In Mosquito Main, Mosquito Tributary and South Bay Dump (Figure 7) very large amounts of sediment are also stored upstream of major -- but less frequently occurring -- log jams.

In unlogged streams, slope appears to be adjusted locally to a combination of log jams and discrete debris steps; in logged and torrented channels, local slope is influenced primarily by log jams. The stability of the unlogged channel should, therefore, be greater because sediment is stored more evenly along the channel, with the many log steps and minor log jams buffering the effects of large flood flows and failure of individual barriers. Large floods in logged channels, on the other hand, may displace infrequent debris obstructions and result in major redistribution of sediment.

The detailed study reaches were examined to quantify the volumes of sediment stored in relation to large organic debris. The LOD maps (Figures 9-16) and large-scale topographic maps (1:200) were used to calculate the volume and position of stored sediment (Table 16).

TABLE 15. Percentage change in channel elevation due to large organic debris steps (channel scale studies)

	Government				Mosquito		South Bay Dump	Hangover	Bonanza[a]	
Reach	A	B	C	D	Main	Tributary	SBD		A	B
Contributing area (km^2)	16.2	6.9	6.8	3.9	10.5	5.4	3.9	20.2	65.4	45.2
Stream order[b]	4	3	4	3	3	3	3	4	5	4
Average gradient	0.0090	0.0125	0.0199	0.0207	0.0092	0.0191	0.0370	0.0125	0.0034	0.0065
Total length of survey (m)	476	981	696	575	1251	479	461	1852	1752	391
No. of LOD steps	3	4	7	3	0	0	2	5	0	4
% change in bed elevation due to LOD steps	6.7	7.7	13.4	8.7	0	0	7.3	9.3	0	14.5

[a] Bonanza A is below the Bonanza-Hangover confluence.
Bonanza B is above the Bonanza-Hangover confluence.
[b] Strahler ordering based on 1:15 000 topographic maps and air photographs.

Both the bankfull width and channel length have been used to standardize the reaches for comparison. The use of the latter method is consistent with most other published results, but it can be used for comparison only when channel gradients and widths are similar.

Review of Table 16 indicates that there are fewer than one-half as many storage sites per channel length in the Mosquito Creek and South Bay Dump reaches as in those of Government Creek. Bonanza Creek has approximately one-third as many storage sites as Hangover. There is no apparent difference, however, in the volume of stored sediment between Government and Mosquito creeks when quantities standardized by channel width are considered; Bonanza has almost 40% more than Hangover. When volumes are standardized by channel lengths of 30 m there appears to be more sediment stored along logged reaches. There is almost 5 times more sediment in South Bay Dump as in Government Reach D. Also, in logged and torrented channels there is more sediment stored upstream of debris jams and relatively less material stored on the downstream side. In contrast, in the unlogged reaches there are considerable amounts of sediment stored on the downstream side of debris pieces. Debris producing a step usually consists of pieces greater than 2 m^3 in volume, oriented predominantly between 80-130° and 230-280°. As the stream flow follows the debris and crosses the channel, sediment accumulates on both sides of the debris.

Both channel and reach scale studies suggest that logged and torrented streams are characterized by larger volumes of sediment stored in fewer zones along the channel. The suggestion that this leads to less stable channels is supported by the generally low stability index rating for these channels and high ratings for unlogged channels (Table 11). Increment cores obtained from trees growing on in-channel debris indicate that certain pieces have residence times in excess of 90 years (Figures 9, 10, and 11) and that all unlogged channels have material with residence times of more

TABLE 16. Volumes of sediment related to large organic debris

Stream reach pairs	Reach length	Bankfull width, W_b	Reach area	Total sediment storage								Sediment storage position[a]			
				Total per reach		Total per area		Total per W_b		Total /30 m channel		Mid-channel		Side channel	
				No. of storage sites	Vol.	No. of storage sites	Vol.	No. of storage sites	Vol.	No. of storage sites	Vol.	Downstream	Upstream	Downstream	Upstream
	(m)	(m)	(m^2)	(no)	(m^3)	(no/m^2)	(m^3/m^2)	(no/W_b)	(m^3/W_b)	(no/30 m)	(m^3/30 m)	(%)	(%)	(%)	(%)
QB	244	20.2	4 398	8	148.6	0.0016	0.0301	0.40	7.36	0.98	17.48	46.5		23.0	30.5
QC	250	21.1	5 268	8	363.9	0.0015	0.0691	0.35	12.25	0.96	41.82	5.0	20.0	36.3	38.7
QD	230	18.8	4 320	5	138.8	0.0012	0.0321	0.27	7.38	0.65	19.28		36.6		63.4
MM	270	37.8	10 154	4	291.1	0.0004	0.0287	0.11	7.70	0.44	30.01			35.5	64.6
MT	223	27.7	6 169	2	240.2	0.0003	0.0389	0.07	8.67	0.27	34.47				100.0
SBD	461	21.0	7 226	3	1 580.1	0.0004	0.2187	0.14	75.24	0.20	102.83	42.5	44.9	6.7	5.9
Hang	261	29.3	7 654	9	430.3	0.0012	0.0562	0.31	14.69	1.03	40.98		56.0	13.3	30.6
Bonz	300	45.4	13 654	6	1 074.6	0.0004	0.0787	0.20	23.67	0.60	99.50		30.3	22.2	47.6

[a] Sediment storage position refers to the location of sediment accumulation; downstream and upstream are with respect to the controlling LOD.

than 40 years. Bonanza Creek has debris with residence times varying between 37 and 68 years (Figure 15), but no large organic debris in either Mosquito Creek reach or South Bay Dump Creek supports living trees. The larger volumes of sediment upstream of debris jams, with the associated lower channel gradients, leads to an increased prevalence of de-watering during low flows in logged channels. For example, during low flow conditions in Mosquito Tributary, surface water is often found only in pools associated with stumps. Similar situations occur in Bonanza Creek.

4.3 Summary

The LOD budget has been altered in logged and torrented channels. More material is floated from upstream in these channels, as opposed to the greater relative importance of material derived from overbank areas in unlogged channels. This change in debris input mechanisms leads to a shift in the size distribution of material stored in the logged and torrented channels. Although the number of pieces is similar in all stream types, there are more large pieces in unlogged channels. Also, the orientation of the stored debris has been changed. The increased frequency of debris oriented parallel to the logged and torrented channels is a further consequence of altered debris input mechanisms (more small debris floated from upstream). The output of LOD is influenced by the change in both input mechanisms and storage characteristics. The material is less stable in logged and torrented channels and the greater mobility of the debris leads to the formation of log jams.

The influence of large organic debris on channel morphology has also been considered. Both the abundance and orientation of the debris are important factors influencing morphology. In zones characterized by abundant debris which diagonally crosses the channel, both the width and depth variability are increased. Also, sediment is stored both upstream and downstream of the debris; qualitative evidence indicates that the downstream sediment is finer in texture. The unlogged streams have more

diverse pool shapes, with long and narrow pools being common, as well as more frequent LOD steps and sediment storage zones, all of which tend to increase channel stability.

In streams with more LOD oriented parallel to the channel -- usually the logged and torrented streams -- width and depth are less variable. Pools are more frequently associated with root wads and stumps. This appears to lead to shorter pools and longer riffles. Furthermore, although channel widening is common after logging and torrenting, LOD appears to influence the recovery process by becoming incoporated into the channel bank and promoting narrowing of the channel. Sediment textures are less variable and fish habitat seems less favourable for several reasons: the lower diversity of features; the larger volumes of sediment stored in fewer zones, which increases the chance of large volumes of sediment moving periodically through the channel; and the increased occurrence of channel de-watering.

5 CONCLUSIONS

This study investigates and compares the morphological character of streams in debris torrented, unlogged (not torrented), and logged (not torrented) watershed channels in the Queen Charlotte Islands. This enables the influence of logging, its related activities, and mass wastage events on channel morphology to be quantified, and provides information concerning appropriate channel stabilization and fish habitat rehabilitation criteria.

The morphological character of a stream channel depends upon the amount, timing, and nature of sediment and water moving through the fluvial system. In turn, the physical components of fish habitats depend largely upon channel morphology. Certain land-use practices that alter the environment, in particular, logging and related activities, have been shown to influence both sediment and water discharge characteristics in many areas: logging and related activities have been associated specifically with changed channel morphology and fish habitat conditions. Because documentation of changes in water discharges and sediment loads is difficult to achieve over time and space, the present study has focussed on the resultant morphological character of logged, unlogged, and torrented watersheds. Rather than evaluating an individual channel dimension such as width, which often has little relevance to fish habitat, this study has concentrated on pool and riffle characteristics. Pools and riffles provide a useful measure of fish habitat and, because they reflect changes in sediment supply to the streams, they provide an indirect indicator of the influence of land-use practices and hillslope processes on channel morphology. In forested watersheds, large organic debris is another independent variable influencing channel shape. This large woody material constitutes a special type of sediment load, with its own input, storage, and output characteristics. It is a factor directly influenced by logging and, hence, is considered in detail in this study.

The study is based on a paired basin design, a preferred approach because it allows a range of areas with different timber harvesting techniques and prevalence of mass movements to be evaluated. The study basins compared have similar geology, climate, soils, and vegetation, but different logging

histories. Because no two basins are exact replicas, it has been necessary to accept certain differences in basin shape as unavoidable. Although basin morphometry is similar in many respects, there are differences which appear to complicate the interpretation of study results. Nevertheless, it has been assumed that any morphological differences between channels within logged and unlogged paired watersheds are due to logging and related activities and/or hillslope processes. To evaluate this assumption the differences in morphological features within one internally homogeneous unlogged watershed were statistically tested. The importance of dissimilar basin morphometries (Table 7) is considered below.

The study conclusions rely on field data obtained over relatively long lengths of channel (channel scale studies) and from fairly short, detailed study reaches (reach scale studies) located within the longer channel segments. Results are summarized in Table 17. The major conclusions are presented in the following paragraphs.

In all channel and reach scale studies there is no significant difference in the morphological features considered among stream segments within the unlogged watershed with internally homogeneous biophysical conditions (Government Creek). This lends credibility to the extensive post-treatment study design and indicates that it is valid to compare channels with different land-use practices and extent of mass wastage, given that other important biophysical conditions are similar.

There are minimal differences in channel and reach scale morphological results between the unlogged and recently logged study areas (Hangover and Bonanza creeks). This suggests that, in this case, contemporary logging practices have resulted in few changes to morphology and habitat. The influence of in-stream large organic debris which was not disturbed during logging appears responsible for preserving pre-logging conditions. Also, because a leave strip was provided, a continued source of LOD is available. This should ensure that minimal changes will occur in the future. It should be noted, however, that several other factors besides logging and related activities may have contributed to the minor differences between Hangover and Bonanza Creeks. First, it is possible that insufficient time has passed since logging for channel changes to occur (logging in the Bonanza watershed had not ceased at the time field work for this report was conducted). Second,

TABLE 17. Summary of channel changes associated with logging and related activities[a]

	Channel comparisons						
General logging status	Not logged	Contemporary logging techniques	Old logging techniques				
Comparison streams	GA, GB, GC, GD	Hang, Bonz	GD, MT	GB, MH	GD, SBD	MT, SBD	GD, MT, SBD
Time since logging (yr)	0	≤ 7	≤ 20	> 20	≤ 20	≤ 20	≤ 20
FFIP stream type[b]	3 3, 2 2	3	2	3	2	2	2
	Channel changes[a]						
Channel scale studies:[c]							
Pool-to-pool spacing	0	0	1	1	•	1	1
Riffle height	0	0	1	1	0	•	1
Relative pool depth	0	0	1	0	•	•	1
Riffle steepness	0	0	0	0	•	•	•
Pool/riffle ratios	0	0	•	•	1	•	1
LOD steps	0	0	•	•	0	•	•
Reach scale studies:[d]							
LOD, number of pieces	0	•	0	•	1	0	1
LOD, volume	0	0	•	•	0	0	0
LOD, orientation:							
Parallel material	0	0	0	1	•	0	•
Perpendicular material	0	0	0	0	•	0	•
LOD, influence on morphology:							
Depth variability	0	0	•	•	1	0	•
Width variability	0	0	•	•	1	0	•
Sediment texture variability	0	0	0	•	•	0	•
Cut banks	0	0	0	•	•	0	•
Prevalent pool type	0	0	0	•	•	0	•
Pool/riffle proportions	•	0	•	0	•	0	•
Stored sediment volume	0	•	•	0	•	0	•
Stored sediment stability	0	0	•	•	•	0	•
Fish habitat as a function of hydraulic conditions:							
Spawning		0					
Fry rearing		•					
Egg incubation		0					
TOTAL							
Quantitative differences	0	0	3	3	4	1	5
Qualitative differences	1	3	9	10	11	5	12

[a] Changes are denoted as follows:
0 = No significant difference (at $\alpha = 0.05$)
1 = Significant difference (at $\alpha = 0.05$)
• = Indication of change but either not significant at $\alpha = 0.05$ or not tested statistically.

[b] FFIP stream type 3 = average channel slope <1°
FFIP stream type 2 = average channel slope 1° - 5°.

[c] Channel scale studies are based on longitudinal surveys conducted over channel lengths in excess of 12 bankfull widths.

[d] Reach scale studies are based on detailed study reaches less than 12 bankfull widths in length.

Bonanza's wide valley flat may slow the timing and reduce the amount of slope material entering the channel (see Table 7). Third, logging extent may be a factor because only 11% of the Bonanza Creek watershed was logged.

In both the unlogged and recently logged watershed channels, the pool-riffle sequence spacing lengths differ significantly from most previously published values. This renders the use of past results to characterize unlogged conditions of minimal benefit. The influence of large organic debris appears to be the factor contributing to atypical values. The LOD also influences sediment areal sorting patterns.

There appear to be more substantial differences in channel morphology and fish habitats associated with older logged or debris-torrented channels, indicated by the relatively high totals corresponding to qualitative and quantitative changes listed in Table 17. The morphological changes in the watersheds logged 20 or more years ago (Mosquito Main and Mosquito Tributary) appear to be due to old, discontinued logging techniques, which included logging to the channel banks and direct disturbance of the channel bed by cross-channel felling and removal of in-stream LOD. The even more pronounced changes in South Bay Dump Creek are due unquestionably to debris torrenting. Both older logged channels are currently experiencing regrowth of riparian vegetation and a reduction in channel widths.

The channel scale studies suggest that channels in watersheds logged by old techniques, or which have been torrented, have reduced pool-riffle spacings and increased riffle heights and altered relative pool depths. This indicates that more sediment has been delivered to the channel than can be moved out of it (transport limited) and, therefore, the material is stored in the riffle zone. The increase in stored sediment results in proportionally larger riffles and smaller pools, and represents a reduction in available rearing habitat. This is more pronounced in torrented channels than in older logged channels. Also, both logged and torrented channels have fewer LOD steps, leading to a shift in the distribution of sediment along the channel and a potential reduction in channel stability.

The reach scale results indicate that LOD characteristics are altered in both the older logged and torrented channels. This includes a shift in the size distribution, with smaller material being more prevalent. Also, there appears to be a change in LOD orientation: more material is lying parallel to the channel and flow direction, as opposed to the more common diagonal orientation found in unlogged channels. Several morphological changes appear to have resulted from the altered LOD character:

1. The variability in channel width and depth and sediment texture is reduced and there are fewer cut banks. This appears to be due primarily to LOD orientation rather than volume. Material lying diagonally across the channel promotes greater variability because of lateral scour across the channel and more efficient trapping of sediment. Material that is oriented parallel to the channel produces longitudinal scour, poor sediment trapping efficiency, and, hence, less variability.
2. The pool area is reduced and pool shape is changed from long and narrow to short and wide. This occurs because pools are associated primarily with LOD oriented parallel to the channel. The pool is produced frequently by scour around the attached root wad.
3. There are larger volumes of sediment, located in relatively few locations, stored along the older logged and torrented channels. In contrast with unlogged channels, where slope is adjusted locally to a combination of minor log jams and discrete debris steps, in older logged and torrented channels local slope is influenced primarily by less frequently occurring major log jams. The stability of these logged channels is less than that of unlogged streams because the displacement of any individual debris obstruction may result in major redistribution of sediments.
4. Fish habitats in the older logged and torrented channels have reduced diversity of flow depths, fewer rearing areas, and less near-bank hiding and resting zones. The channel substrate is less stable, which may influence egg incubation suitability. The larger volumes of sediment lead to increased occurrence of de-watering during low flow conditions.

As indicated throughout this report, an inability to fully account for all independent variables has led to the possibility that certain documented morphological differences between unlogged and logged channels are due, to some extent, to factors other than land-use practices (Table 7). It is clear from Table 7 that only basin morphometric variables differ between comparison channels. The importance of a larger drainage basin and flat valley bottom in Bonanza, compared to Hangover, is that the influence of logging and related activities on channel morphology may be delayed. In this case, basin size and shape influences the timing of channel changes and suggests that a longer study duration is advisable. The differences in basin relief, shape, slope, and valley bottom extent evident in the older logged basins indicate that these factors require more attention before definitive conclusions can be presented. The importance of these variables to the present study is that the steeper basin slopes in Mosquito Creek may increase the transfer rates of sediment from the slopes to the channel, thus influencing channel morphology. The importance of these variables as complicating factors cannot be quantified in the present study. Quantification of the relative importance of different morphometric properties and the development of a scheme to determine systematically if basins are suitably matched could be the focus of future studies.

Based on the natural channel morphology in the unlogged and recently logged channels (Government, Hangover, and Bonanza creeks), it is possible to outline the conditions that might be "duplicated" in attempts to rehabilitate disturbed third- to fifth-order coastal stream channels (from 1:15 000 and 1:20 000 maps and aerial-photographs; or, first- to third-order on 1:50 000 maps). These conditions, which are not influenced by problems associated with basin morphometry, include the following:

1. Pool and riffle sequences should be spaced such that their average length is equal to 2 to 3 channel widths.
2. Relative pool depths should average approximately 0.010 m/m to 0.015 m/m (pool depth/pool-riffle length) and their riffle steepness values should be between 0.021 m/m and 0.026 m/m (pool depth/pool-riffle length).

3. Large organic debris should play a major role in rehabilitation; only large pieces (lengths equal to the channel width, and/or volumes greater than 3 m^3) should be used. Long pieces of debris should be placed diagonally across the channel, with the root wad close to the bank and on the downstream end, to increase depth variability and store sediment on both the upstream and downstream sides. LOD should be placed parallel to the flow if channel widths are to be reduced and riparian vegetation regrowth is to be encouraged. Large root wads should be placed between the diagonally crossing material to produce smaller scour holes (as opposed to scour pools).
4. If large organic debris steps are to be placed in the channel, they should consist of several small steps accounting for only about 10% of the overall change in elevation.
5. Large clusters of organic debris should not be placed closer than approximately 3.5 channel widths apart.

The use of published geomorphic results to characterize unlogged watershed channels is not practical because the influence of large organic debris has not been thoroughly considered in previous studies. The present work begins to identify possible patterns of LOD and its influence on channel morphology and fish habitat.

Several important issues that have not been adequately dealt with have been identified during the course of this study. Because these problems have not been resolved, it is recommended that each be the focus of a future investigation:

1. In the present study, the time since logging and/or debris torrenting was shown to be an important independent variable influencing channel morphology characteristics. From a resource management perspective, it is important that more work be carried out to assess the rate and process of channel recovery in Queen Charlotte Islands streams.
2. Basin morphometry has been cited as a critical factor contributing to channel form. Before post treatment-event (synoptic) studies, such

as the Fish/Forestry Interaction Program (FFIP), can be evaluated accurately, a method to determine basin morphometric similarity must be developed.

3. Longer reaches are recommended for study so that certain channel features can be investigated more thoroughly (e.g., channel width variability, the spatial nature of LOD clustering, and the influence of LOD on vertical and horizontal channel stability). For practical purposes a different, less time intensive field technique than that used in this study will be needed to survey longer stream reaches. Very low level air photography techniques (e.g., using helium balloon platforms) should be considered.
4. A review of appropriate statisical techniques should be undertaken. The FFIP studies rely on the 95% confidence limit to determine whether hypotheses are accepted or rejected. In this study it was determined that a significant difference exists at the 95% confidence level in certain morphological features between unlogged, logged, and torrented channels, but the difference is insignificant at the 99% confidence level (e.g., pool/riffle ratios and relative pool depths, see Hogan 1985). The selection of appropriate confidence levels must be reviewed and justified.

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APPENDIX 1. Statistical procedures and summary tables of field data and analysis of variance results

Statistical Procedures

In this report inferential statistics are used in two situations: first, to determine if a significant difference exists between watersheds (watershed comparability); and second, to determine if a significant difference exists in channel morphology between streams (effect of land-use practices). The first situation is intended to ensure that basins are comparable with respect to several biophysical conditions. Here one is more willing to accept a type 1 error, hence a confidence limit of 90% appears reasonable. However, in the second situation, where conclusions refer to land-use practices, a type 1 error is less acceptable and a more stringent confidence level is warranted. In this case a confidence limit of 95% appears appropriate and therefore is used in this study.

Field Data and Analysis of Variance Test Results

The following tables and figure include complete field data and statistical information.

TABLE A1. Summary of pool-riffle proportions for individual study channels

Individual channels

	Stream channels								
	GA	GB	GC	GD	MM	MT	SBD	Hang	Bonz
Survey length (m)	476	981	697	575	1251	479	471	1844	2143
Average channel gradient	0.0090	0.0125	0.0199	0.0207	0.0092	0.0191	0.	0.0125	0.0048
Pool (%)	60.2	47.2	50.2	47.8	28.3	32.5	11.3	21.8	51.8
Riffle (%)	39.9	24.1	25.4	37.4	52.1	56.9	85.5	37.4	35.2
Glide (%)	0	14.8	15.0	11.4	13.7	6.3	3.3	23.9	6.7
Run (%)	0	14.0	9.5	3.4	6.0	4.3	0	16.9	9.7
Pool + guide (%)	60.2	62.0	65.2	59.2	41.9	38.8	14.6	45.7	58.5
Riffle + run (%0	39.9	38.1	34.9	40.8	58.1	61.2	85.5	54.3	44.9

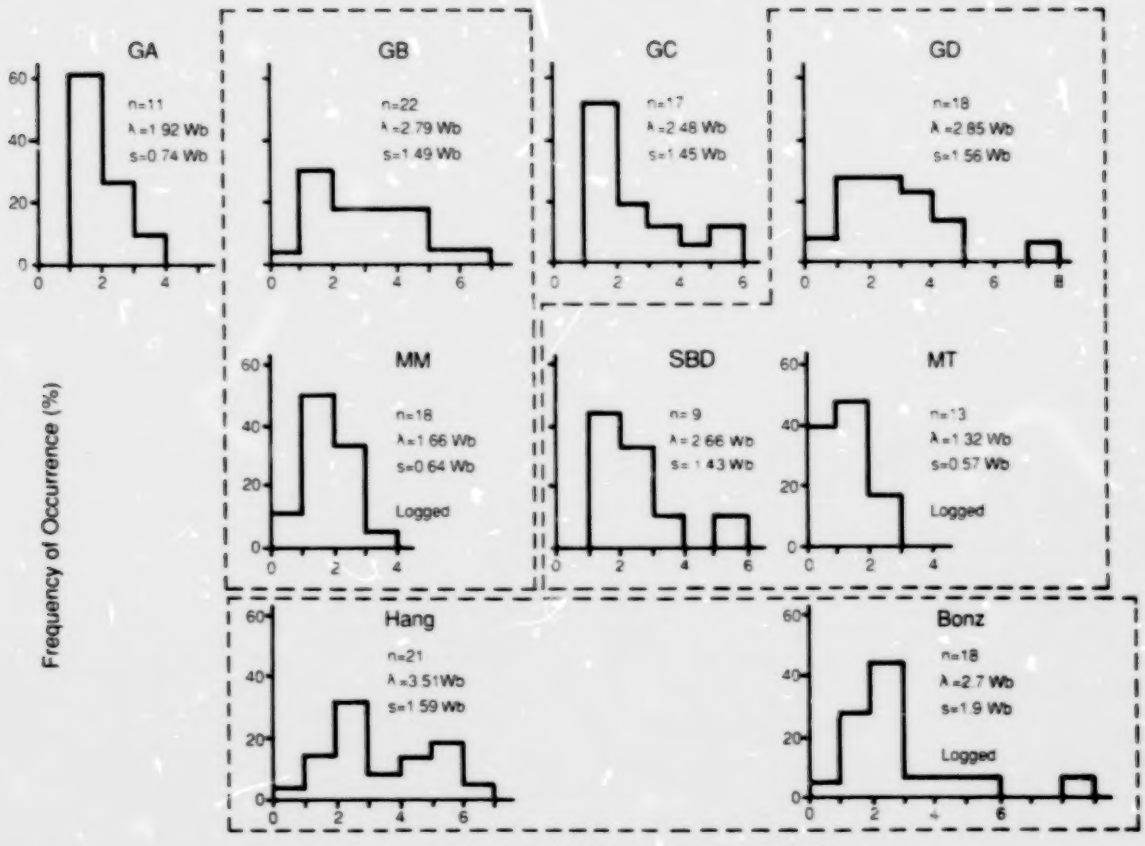
Pool/riffle ratios by stream channel

Channel	GA	GB	GC	GD	MM	MT	SBD	Hang	Bonz
$\frac{\sum_{i=1}^{n} L_{Pi}}{\sum_{i=1}^{n} L_{Ri}}$	1.51	1.63	1.87	1.45	0.72	0.63	0.17	0.84	1.30
$\sum_{i=1}^{n} \frac{(L_{P_i})}{L_{R_i}} \Big/ n$	1.16	3.01	3.01	4.43	1.33	0.94	0.27	1.52	2.17

TABLE A2. Summary of analysis of variance results for pool/riffle ratios

Stream channels compared	Degrees of freedom Between	Within	F	$F_{(\alpha=0.05)}$	Decision
Within-basin comparison:					
GA, GB, GC, GD	3	60	1.49	2.76	Accept H_0
Between-basin comparisons:					
GB, MM	1	38	4.52	4.10	Reject H_0
GD, MT	1	31	3.60	4.16	Accept H_0
GD, SBD	1	25	7.47	4.25	Reject H_0
MT, SBD	1	20	5.98	4.35	Reject H_0
GD, MT, SBD	2	37	5.32	3.26	Reject H_0
Hang, Bonz	1	37	1.22	4.11	Accept H_0

H_0 = there is no significant difference (α = 0.05) in mean pool-riffle proportions.



n=Number of Pool-Riffle Sequences
λ=Mean Spacing in Bankfull Widths (Wb).
s=Spacing Standard Deviation.

FIGURE A1. Frequency distribution of pool-riffle spacing for five unlogged watershed streams and four logged watershed streams.

TABLE A3. Summary of analysis of variance results for pool-riffle spacing

Stream channels compared	Degrees of freedom Between	Within	F	$F_c(0.05)$	Decision
Within-basin comparison:					
GA, GB, GC, GD	3	64	1.21	2.73	Accept H_0
MM, MT	1	30	2.52	4.17	Accept H_0
Between-basin comparisons:					
GB, MM	1	38	8.85	4.10	Reject H_0
GD, MT	1	29	11.51	4.19	Reject H_0
GD, MT, SBD	2	37	5.80	3.26	Reject H_0
GD, SBD	1	25	0.10	4.25	Accept H_0
MT, SBD	1	20	9.43	4.35	Reject H_0
Hang, Bonz	1	38	1.98	4.10	Accept H_0
Unlogged, logged	1	136	10.59	3.92	Reject H_0
Unlogged, logged, and torrented	1	156	44.69	3.91	Reject H_0
Adjusted width:					
GB, MM	1	38	0.01	4.10	Accept H_0
GD, MT	1	29	2.83	4.19	Accept H_0
GD, MT, SBD (unadjusted)	2	37	1.41	3.26	Accept H_0
GD, SBD (adjusted)	1	25	2.30	4.25	Accept H_0
Influence of LOD:					
GA, GB, GC, Hang, Sachs	4	88	11.57	2.51	Reject H_0
GB, Sachs	1	42	16.05	4.08	Reject H_0
Hang, Sachs	1	41	10.20	4.08	Reject H_0

H_0 = there is no significant difference, at $\alpha = 0.05$, in mean spacing of pools.
F_c = critical F-test value for a probability level of 95%.

TABLE A4. Summary of channel-averaged riffle height, relative pool depth, and riffle steepness

Channel	GA	GB	GC	GD	MM	MT	SBD	Hang	Bonz
Riffle height (m)									
Average	0.251	0.305	0.390	0.324	0.667	0.662	0.440	0.618	0.681
Standard deviation	0.205	0.181	0.249	0.231	0.371	0.273	0.202	0.283	0.302
Relative pool depth (m/m)									
Average	0.0095	0.0163	0.0114	0.0101	0.0128	0.0200	0.0112	0.0113	0.0112
Standard deviation	0.0059	0.0106	0.0074	0.0053	0.0065	0.0119	0.0068	0.0098	0.0109
Riffle steepness (m/m)									
Average	0.0264	0.0214	0.0229	0.0315	0.0211	0.0295	0.0133	0.0225	0.0262
Standard deviation	0.0257	0.0204	0.0161	0.0259	0.0116	0.0160	0.0094	0.0229	0.0294
Average channel gradient	0.0090	0.0125	0.0199	0.0207	0.0092	0.0191	0.0366	0.0125	0.0048

TABLE A5. Summary of analysis of variance for riffle height, relative pool depth, and riffle steepness

Stream channels compared	Degrees of freedom Between	Within	F	$F_c(0.05)$	Decision
Within-basin comparison:					
GA, GB, GC, GD					
Amplitude	3	60	0.52	2.76	Accept H_0
Magnitude	3	60	0.32	2.76	Accept H_0
Relative relief	3	60	0.72	2.76	Accept H_0
Between-basin comparisons:					
GB, MM					
Riffle height	1	42	15.94	4.08	Reject H_0
Relative pool depth	1	42	8.36	4.08	Reject H_0
Riffle steepness	1	42	0.004	4.08	Accept H_0
GD, MT					
Riffle height	1	24	11.68	4.26	Reject H_0
Relative pool depth	1	24	8.18	4.26	Reject H_0
Riffle steepness	1	24	0.04	4.26	Accept H_0
GD, SBD					
Riffle height	1	22	1.54	4.30	Accept H_0
Relative pool depth	1	22	3.14	4.30	Accept H_0
Riffle steepness	1	22	4.14	4.30	Accept H_0
MT, SBD					
Riffle height	1	18	4.10	4.41	Accept H_0
Relative pool depth	1	18	4.00	4.41	Accept H_0
Riffle steepness	1	18	6.55	4.41	Reject H_0
GD, MT, SBD					
Riffle height	2	32	6.43	3.30	Reject H_0
Relative pool depth	2	32	4.36	3.30	Reject H_0
Riffle steepness	2	32	2.52	3.30	Accept H_0
Hang, Bonz					
Riffle height	1	39	0.40	4.08	Accept H_0
Relative pool depth	1	39	0.27	4.08	Accept H_0
Riffle steepness	1	39	0.21	4.08	Accept H_0

H_0 = there is no significant difference ($\alpha = 0.05$) in mean riffle height, steepness and pool depth.

TABLE A6. Summary of analysis of variance results for large organic debris volumes

Stream channels compared	Degrees of freedom Between	Degrees of freedom Within	F	$F_c(0.05)$	Decision
Within-basin comparison:					
GB, GC, GD	2	631	0.33	3.00	Accept H_0
Between-reach comparisons:					
GB, MM	1	442	4.22	3.84	Reject H_0
GD, MT	1	470	7.58	3.84	Reject H_0
GD, SBD	1	637	22.11	3.84	Reject H_0
MT, SBD	1	743	3.28	3.84	Accept H_0
GD, MT, SBD	2	925	10.87	3.00	Reject H_0
Hang, Bonz	1	335	1.96	3.84	Accept H_0

H_0 = there is no significant difference, at $\alpha = 0.05$ in the mean volume of large organic debris.

TABLE A7. Summary of textural analysis[a] of surface, subsurface, and McNeil sediment samples (phi units)

Stream reach	Sample[b] Type	No.	Percentile D_{50}	Finer D_{90}	Mean	Standard deviation	Skewness	Kurtosis
GB	SS	1	-4.32	-5.74	-3.79	-1.96	-0.40	0.95
	S	1	-4.86	-6.67	-4.94	-1.27	0.09	0.95
	S	2	-4.81	-9.09	-4.84	-1.01	0.05	0.87
	S	3	-5.06	-6.12	-5.00	-0.95	-0.10	0.77
GC	SS	1	-4.87	-6.15	-4.48	-1.81	-0.32	1.00
	S	1	-5.31	-6.61	-5.23	-1.04	-0.11	1.07
	S	2	-4.58	-6.93	-4.77	-1.30	0.21	0.95
	S	3	-6.17	-7.25	-6.09	-0.93	-0.13	1.13
GD	SS	1	-5.15	6.18	-4.49	-1.98	0.50	0.87
	S	1	-6.17	-8.06	-6.50	-1.49	-0.21	0.95
	S	2	-5.64	-8.30	-6.06	-1.75	0.36	0.90
MM	S	1	-5.67	-7.01	-5.58	-1.22	-0.11	0.91
	S	2	-5.77	-7.02	-5.67	-1.19	0.12	0.99
	S	3	-5.22	-6.58	-5.39	-1.04	-0.19	0.97
MT	SS	1	-5.66	-6.19	-4.73	-1.88	-0.74	1.14
	S	1	-6.54	-7.40	-6.44	-0.84	-0.18	1.20
	S	2	-6.24	-7.60	-6.20	-1.22	-0.04	0.97
	S	3	-5.57	-6.75	-5.51	-1.34	-0.07	0.84
SBD	SS	1	-.388	-6.19	-3.91	-2.12	0.02	0.88
	S	1	-5.88	-6.49	-5.53	-0.87	-0.09	0.90
	S	2	-5.75	-7.21	-5.72	-1.21	-0.04	0.86
	S	3	-6.41	-7.92	-6.29	-1.23	-0.14	0.91
	S	4	-5.70	-7.36	-5.66	-1.46	-0.04	0.80
Hang	SS	1	-4.29	-5.86	-3.79	-2.12	-0.35	0.91
	S	1	-5.80	-6.62	-5.70	-0.80	-0.20	0.96
	S	2	-5.84	-6.74	-5.69	-0.86	-0.27	0.75
	M	1	-5.11	-6.27	-4.82	-1.48	-0.29	1.13
	M	2	-4.43	-6.35	-4.21	-2.16	-0.15	0.87
	M	3	-3.95	-5.77	-3.52	-2.00	-0.33	0.87
Bonz	SS	1	-4.11	-5.80	-3.67	-2.11	-0.31	0.90
	S	1	-5.32	-6.39	-5.31	-0.87	-0.02	0.99
	S	2	-5.19	-6.26	-5.13	-1.00	-0.08	0.78
	S	3	-4.58	-5.47	-4.60	-0.68	0.06	1.01
	S	4	-5.31	-6.00	-5.15	-0.82	-0.28	0.80
	M	1	-3.53	-4.61	-3.33	-1.30	-0.23	1.02
	M	2	-3.25	-4.61	-2.91	-1.79	-0.29	0.87
	M	3	-3.88	-4.65	-3.66	-1.05	-0.32	1.04

[a]Textural analysis based on graphic measures after Folk and Ward (1957) where:

mean size = $(\phi_{16} + \phi_{50} + \phi_{84})/3$

standard deviation = $(\phi_{84} - \phi_{16})/4 + (\phi_{95} - \phi_{5})/6.6$

skewness = $[(\phi_{16} + \phi_{84} - 2\,\phi_{50})/2(\phi_{84} - \phi_{16})] = [(\phi_{5} + \phi_{95} - 2\phi_{50})/2(\phi_{95} - \phi_{50})]$

kurtosis = $(\phi_{90} - \phi_{1})/1.9(\phi_{75} - \phi_{25})$

and where

ϕ_n = the grain size (in phi units) at which n percent of the distribution is coarser

$\phi = -\log_2 mm$

[b]Sample type: SS = subsurface bulk; S = surface transect; M = McNeil bulk riffle sample
Sample no: refers to locations in Figures 10 - 16; No. 1 is at the downstream end of the reach in all cases.